TECHNOLOGY UTILIZATION

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THERMAL INSULATION SYSTEMS

A SURVEY

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Foreword

Thermal insulation systems are extending the range of temperatures attainable and maintainable in industrial operations. The exploration of space has necessitated acceleration of development of materials and combinations of materials to shield men and machinery in both extremely cold and extremely hot environments.

The information and data acquired by National Aeronautics and Space Administration researchers and contractors also can be used in a multitude of other ways. This is a guidebook to this new resource, prepared by Dr. Peter E. Glaser and his colleagues at Arthur D. Little, Inc., for the space agency's Office of Technology Utilization. It is one of a series of such publications intended to help persons who are not engaged in aerospace work benefit from the advances in technology resulting from such work.

There have been many advances in thermal insulation in which NASA has had no part; this book focuses attention on those related to the space agency's programs.

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Introduction

The purpose of this survey is to summarize, and thus make more accessible to industry, data on the performance of thermal insulations and systems combining such insulations, particularly for cryogenic applications, and to indicate opportunities for improvements.

Better thermal insulations have been developed to meet the growing demands of industry. Without the availability of suitable thermal insulations, development of most processes where conservation of heat energy governs the overall efficiency would have been significantly retarded. For example, the expansion of the food preservation and distribution industries, which once relied on river or pond ice insulated with wood and sawdust, would not have been possible without refrigerating machinery and storage facilities insulated with such new materials as fiber glass or foam. Because thermal insulations are so important in industrial practice, new developments in insulation materials are frequently followed by the introduction of new processes, which, in turn, result in a general advance in technology.

One of the most striking examples of the direct effect of the availability of new insulations on technology is the growth of the cryogenic industry in the last 10 years. This industry's extensive employment of refrigeration, liquefaction, transportation, and storage of gases at very low temperatures is directly traceable to the development of highly effective thermal insulations. Cryogenic fluids that once were laboratory curiosities, such as liquid methane, oxygen, nitrogen, hydrogen, and helium, have become commonplace not only in the laboratory but also in large-scale industrial operations.

The striking advances in the effectiveness of thermal insulations can be directly attributed to the concentrated development efforts in support of the national space exploration program. The starting point for these advances was the double-wall, vacuum-insulated glass Dewar flask. The Dewar flask was widely used to

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store cryogenic fluids until the demand for cryogenic fluids, particularly liquid oxygen and liquid hydrogen, as fuels for space vehicles, became significant. Insulation developments resulting from space programs have provided a firm base on which industry can build in meeting the needs to protect cryogenic fluids, refrigerated components, and similar devices from the heat transferred by the surrounding environment.

The advances in thermal insulations, though primarily for applications at cryogenic temperatures, have also influenced the development of thermal insulations for use at higher temperatures. Different materials must be selected to withstand higher temperatures, but similar principles of heat transfer apply. The thermal insulations available today fall into two major categories: insulations which are gas filled, and insulations in which the gas has been evacuated to achieve a required low pressure. Figure 1 shows the effectiveness of different classes of insulating materials (foam, powder, fiber, and multilayer insulations) which span a range of more than 3 orders of magnitude of thermal conductivity.

Although multilayer insulations are the most striking of the important new developments, space-oriented programs have also resulted in improvements in the effectiveness of foam, evacuated powder, and fibrous insulations. Experience has been gained in their applications. Several of these new insulations are being
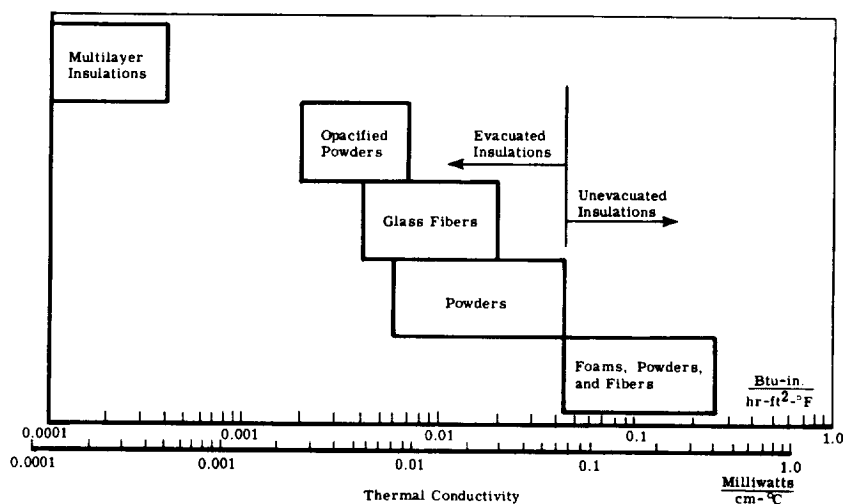
FIGURE 1.—Thermal conductivity of thermal insulation materials. (Temperature range: 60° to −320° F (238° to 77° K); density range: 2 to 5 lb/ft^3 (0.03 to 0.08 g/cm.^{3}))

used now in industry and are shortening the normal time associated with new product development.

Information on thermal insulations developed in the course of space research programs has been made available to scientists and engineers in the aerospace industry through contractor reports and technical articles in professional journals. This information has not yet been fully exploited, primarily because relevant parts of it have been difficult to extract. Much of it is fragmented in the various reports that describe the development of space vehicles, their components, and the research that supports such developments. Hence, there has been insufficient awareness that valuable information, which can be applied in commercial product areas, has been generated.

In the following chapters we discuss possible uses of thermal insulation systems in industry; the principles of thermal protection systems; insulation components for such systems; and their integration, installation, and performance in typical applications. In this discussion we assume that the reader has a basic knowledge of the principles of heat transfer.

Applications of Thermal Insulations

GENERAL APPLICATIONS

The development of thermal insulations and their dramatic impact on advances in technology can be seen most readily in the aerospace industry, where applications include the whole range of thermal insulations for space-vehicle cryogenic fuel stages, engine components, instruments, space suits, and electronic devices. However, much industrial cryogenic work remote from the space effort also requires very effective thermal insulation systems. For example:

Liquefaction of Natural Gas

The availability of liquefied natural gas has dramatically altered the industrial potential of countries deficient in fossil fuels and has increased the utilization of the world's natural gas reserves. Only a few years ago, natural gas was burned as a waste product of oil wells, gasfields, and refineries. It is now liquefied and transported to distant points for use as fuel—liquefied-methane tankers, for example, supply England with fuel from North Africa. Oceangoing tankers have used thermal insulations such as PVC-type foam, glass wool, balsa wood, and perlite.

The discovery of natural gas in the North Sea promises to have an important effect on the neighboring countries. Because of the relatively short distances involved, carrying liquefied natural gas to major distribution points via pipelines is now being considered. To reduce boiloff losses such pipelines could be insulated with evacuated powder or multilayer insulations.

During World War II gasoline shortages, methane was used as a fuel for London buses. Increased availability of liquefied natural gas may make such uses of methane more competitive. Methane has also been considered as a fuel for commercial supersonic aircraft. Its use would enhance combustion efficiency, and its availability in many areas of the world would ease logistics

problems. Analysis has shown that a payload improvement up to 31 percent and an operating cost reduction of up to 36 percent might be realized with methane. A thermal protection system would have to be devised to allow liquefied methane to be carried in the wing of the aircraft. Among the systems considered for this purpose are evacuated powder, fiber glass, and multilayer insulations (ref. 1).

Thermal insulation is being applied to the inside of large-capacity concrete tanks designed to store liquefied natural gas for peak load sharing in city gas supply systems during winter. Placing the thermal insulation on the inner surfaces of a tank provides the advantage of rapid, low-loss-rate cooldown, smaller thermal expansion or contraction of the wall, and greater protection from mechanical damage to the insulation during operation. A flexible laminate of aluminum, Dacron, and Mylar forms the protective cover for the insulation. This thermal insulation system can be compared with the approach used for the internal insulation of the Saturn rocket's S–IV stage for liquid hydrogen. It appears likely that techniques established for the space booster can aid in applications of insulations to large terrestrial storage tanks.

Generation and Transmission of Electricity

The consumption of cryogenic liquids by the electrical industry is expected to increase as developments of superconductors for electric motors, generators, transformers, and magnets reach the practical stage. The use of superconducting materials, requiring temperatures from 7° to 36° R (4° to 20° K) to be maintained around conductors, will reduce the electrical power losses in cables and the various devices. These low temperatures may be achieved by the circulation of cyrogenic fluids, such as helium or hydrogen, which, in turn, will require highly effective insulations to keep external heat inputs minimal.

As power demands in large cities increase, cooling of underground electrical cables will become increasingly important. Conventional cables buried in the soil beneath city streets require that the subsoil absorb the heat generated within the cable and conduct it away at a rate sufficient to prevent overheating of the cables. With increased power requirements, this natural heat transfer is inadequate. Therefore cooling of electrical cables with fluids such as oil, Freon, nitrogen, hydrogen, or helium is being considered. Such coolants will require the installation of underground insulated fluid lines to maintain the desired temperatures in the cables.

Electronic Equipment

The maintenance of low temperatures to diminish noise in electronic devices such as communication antennas has considerable practical importance. To minimize the refrigeration required to keep such devices at the desired low operating temperatures, effective thermal insulations, usually of the multilayer type, have been used. In most instances the insulations are incorporated in the overall design of the device and the associated cooling system; one example is the cryodyne refrigerator.

Effective insulations are also important in electrical devices that must operate over a range of temperatures and still maintain a closely controlled operating temperature; for example, crystal ovens which have to maintain a preset temperature even when exposed to arctic environment. Multilayer insulations applied to such ovens have reduced power requirements by a factor of 20 and at the same time have reduced the size of the devices. A similar application for multilayer insulation was in a balloon-borne fuel cell which had to operate for extended periods of time.

Thermal insulations have extended the unattended operating periods of remotely located instruments that rely on battery power to control and maintain the desired operating temperature. Examples include batteries designed for arctic use, gravimeters for geophysical explorations, oceanographic instruments placed at great depths, and balloon-borne meteorological instruments.

Manufacturing Processes

In manufacturing plants, the steadily increasing use of cryogenic fluids has brought about the need for insulation of large storage tanks and pipelines. Oxygen is used in a newly developed steelmaking process. Uses of liquid nitrogen include the stiffening of organic materials (e.g., rubber) to permit precise machining and the cryogenic forming of metals to achieve high strength. In the future, liquid nitrogen also may be used to prepare scrap metal for pulverization by cooling it to the low temperatures at which it becomes brittle.

The use of liquid helium in manufacturing processes has increased since large centralized helium liquefaction plants have been built. Today, liquid helium rather than compressed gas is being used for many applications, for example, in the electronics industry. Shipment of helium has been made possible by the application of multilayer insulation to liquid helium storage containers. Shipment of liquefied helium is, of course, more efficient

than shipment of compressed gas, which requires heavy cylinders limiting the amounts of helium that can be transported.

Similarly, the use of different liquefied gases has been made possible by the availability of storage tanks with more effective thermal insulations. Such storage tanks permit the widespread distribution of gases for industrial purposes such as welding and cutting.

Medicine

The use of cryogenic fluids in the medical sciences is increasing and thermal insulations will be needed increasingly for preservation of blood, organs, and tissues. In the future, surgical procedures may be bloodless when tissues in the vicinity of the operating area can be frozen with liquid nitrogen. Liquid nitrogen probes are already being used in specialized surgical procedures, such as brain operations.

Other Applications

Multilayer insulations have been used in the fabrication of a rescue blanket that can reflect up to 90 percent of the body heat. Such a blanket is nearly weightless; it can be packed in a volume equivalent to that of a cigarette package; and it is flexible, windproof, waterproof, washable, and capable of holding the weight of a 200-pound man. This type of blanket has a wide variety of uses where protection from a cold environment is desired.

Flexible multilayer insulations which may either be erected by gas pressure or draped around an existing structure are being investigated for possible uses as lightweight disposable thermal insulations for frozen food, air shipment of produce, and protection of other perishable goods.

Fuel cells and electrical batteries being developed to power electrical cars of the future can be operated effectively only at elevated temperatures. To reduce fuel or power consumption, highly effective thermal insulations will be required.

TYPICAL SPECIFIC COMMERCIAL APPLICATIONS

Crystal Oven

A crystal oven with a volume less than 3 in.³ has been designed to maintain a quartz crystal at 167° F (75° C) while exposed to an environment with a minimum ambient temperature of −58° F (−50° C) (ref. 2). A 50-milliwatt electric heater

maintains the desired temperature in a cavity ¾ inch in diameter by 1 inch long.

The performance of various multilayer insulations under these conditions can be estimated from the data presented in chapter 4, page 39. For example, an insulation consisting of alternating layers of 0.02-inch-thick aluminum radiation shields and 0.04-inch-thick fiber glass paper reduces the heat flux through a ¼-inch-thick layer to 0.22 Btu/hr-ft² (70 mW/cm²), measured between 68° and 320° F (20° and −196° C).

Since the warm-boundary layer in the oven is 167° F (75° C) rather than 68° F (20° C), the heat flux will increase in proportion to the ratio of the fourth power of the warm-boundary temperatures:

$$\frac{(75+273)^4}{(20+273)^4} \sim 2$$

If a load-supporting insulation (ch. 5, p. 89) is selected, the decrease in the insulation performance due to any particular load can be predicted by using the relation of the proportionality of the heat flux to the two-thirds power of the compressive load. The actual heat flux is then equal to the heat flux through the insulation at no external load (load is applied only by the weight of insulation) multiplied by the two-thirds power of the ratio: load per unit area applied to the insulation divided by one-half the weight per unit area of the insulation. Thus, for this example, a fifteenfold increase in heat flux is obtained. The twofold increase in the heat flux due to the increase of the warm-boundary temperature makes the total expected increase in the heat flux 30 times greater than the heat flux through the same insulation (measured with no compressive load and between 68° and −320° F (20° and −196° C)).

The heat loss is expected to be 0.14 Btu/hr (40 mW) through a ¼-inch-thick evacuated multilayer insulation.

Table 1 shows test results of the ovens using various insulations. All ovens were 3 in.³ in volume, with ¼-inch-thick insulation space. The performance of all ovens was close to theoretical predictions. A typical oven is shown in figure 2. Figure 3 shows the construction of the multilayer insulation.

Liquid-Hydrogen Transporter

The increasing use of liquefied gases has necessitated transporting them in considerable quantities. A liquid-hydrogen transporter capable of carrying 12 000 gallons (45 m³) has been developed (fig. 4). The tank was designed to take advantage of the

TABLE 1.—*Test Results of Experimental Crystal Ovens*

Physical data

Oven volume	3 in.³ (49 cm³)
Cavity size	0.5 in.³ (8 cm³)
Insulation thickness	¼ in.
Ambient temperature	−58° ± 9° F (−50° ± 5° C)
Oven temperature	+167° ± 9° F (+75° ± 5° C)
Vacuum in the insulation space	Below 1 × 10⁻⁴ torr

Performance data

Type of insulation	Required power, W
Vacuum	0.24
Mixture of silica and carbon powders	.12
25 layers of 0.004-in.-thick fiber-glass paper	.12
16 layers of 0.002-in.-thick tempered aluminum } 15 layers of 0.004-in.-thick fiber-glass paper }	.040

maximum dimensions allowed by the Interstate Commerce Commission (40 ft long by 8 ft wide by 12.5 ft high).

Maximum volume within these dimensions is achieved for the liquid-hydrogen contents by the use of multilayer insulation. This insulation minimizes the space between the cold wall and the outer wall of the tank while maintaining a specified heat loss (0.33 percent) (ref. 3).

The heat flux for the uncompressed insulation system was predicted from tests made with a flat-plate calorimeter to be 0.14 Btu/hr-ft² (44 mW/cm²) (ref. 4). Tests of the liquid-hydrogen filled transporter showed the total heat loss to be 192 Btu/hr
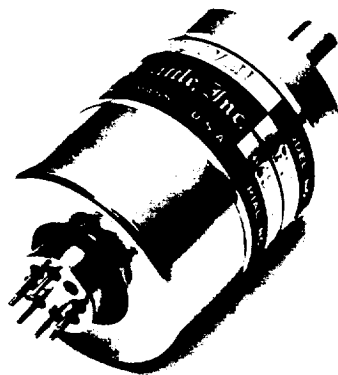
FIGURE 2.—Typical crystal oven.
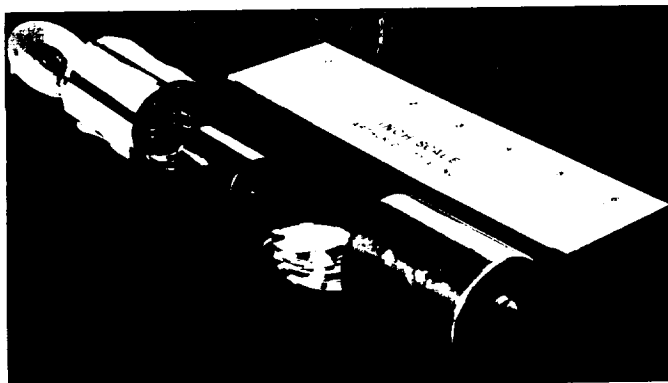
FIGURE 3.—Crystal oven with multilayer insulation.

(56 W), including losses through piping and support systems. The support system and piping may contribute as much as 45 Btu/hr (13 W) to the total heat loss. Thus, the actual heat flux through 1000 ft^2 area of insulation is estimated to be 0.147 Btu/hr-ft^2 (46 mW/cm^2).

Transportable Cryogenic Liquid Storage Vessel

Many Dewar vessels—an inner and outer shell with the space between evacuated and sealed—are in use today. Most of these vessels, however, are not particularly rugged in construction; they cannot be readily handled or transported by airplane. An improved Dewar-type cryogenic liquid container has been built that can withstand 10-g accelerations (or a considerable amount

FIGURE 4.—Liquid-hydrogen transporter (12 000-gallon capacity).

FIGURE 5.—Cryogenic liquid
container.

of handling) and can be fabricated in sizes ranging from 25 to
800 gallons (ref. 5). The vessel (fig. 5) has highly effective insu-
lation that minimizes the boiloff rate of the stored cryogenic
liquid and makes it possible for the cryogenic fluid to be lique-
fied directly in it.

An inner vessel contains the cryogenic liquid; an outer vessel
surrounds this inner shell to form an evacuable space. Within
this space and surrounding the inner vessel is a cooled radiation
shield, around which is wrapped a 15-layer insulation. The multi-
layer insulation consists of layers of aluminum foil and vinyl-
coated fiber-glass screen.

Maximum use of the refrigeration capacity of the boiloff gases
is achieved by using the boiloff vapors to cool the radiation
shields and the neck tube. Lateral supports of low-thermal-con-
ductivity fiber-glass-reinforced epoxy, equally spaced at the top
and bottom of the vessel, connect the radiation shield to the outer
shell. The positioning of the inner vessel inside the radiation
shield at the bottom is accomplished with a glass-ball support.

Highly effective proprietary designs of cryogenic storage and
transport vessels have been developed by industrial companies.
Significant internally sponsored development work has been
carried out by such companies (ref. 6). The additional experience
gained by these companies on space-oriented programs is re-
flected in a more rapid advance in product improvement and de-
velopment as well as the more effective performance of avail-
able industrial equipment.

Principles of Thermal Insulation Systems

DEFINITIONS

Thermal insulations consist of either a single material, a mixture of materials, or a composite structure, and are designed to reduce heat flow between their boundary surfaces at specified temperatures. The effectiveness of a thermal insulation is judged on the basis of thermal conductivity, which depends on the physical structure of the material.

"Thermal conductivity" is defined as the property of a homogeneous body measured by the ratio of steady-state heat flux (time rate of heat flow per unit area) to the temperature gradient (temperature difference per unit length of heat-flow path) in the direction perpendicular to the area. A material can be considered homogeneous when the value of thermal conductivity is unaffected by variations in specimen thickness or area over a small temperature range.

To be meaningful, thermal conductivity must be identified with respect to the mean temperature. For a material that is not isotropic, thermal conductivity varies not only with temperature but also with the direction and orientation of heat flow. Thermal conductivity is usually measured with a material exposed to a definite temperature difference. Because of the complex interactions of several heat-transfer mechanisms, the term "effective" or "apparent" thermal conductivity is employed to distinguish this value from an ideal thermal conductivity corresponding to a very small temperature difference.

In general, the performance of a thermal insulation depends on the temperature and emittance of the boundary surfaces, its density, the type and pressure of gas contained within it, its moisture content, its thermal shock resistance, the compressive loads applied to it, and the effects of mechanical shocks and vibrations.

"Emittance" is the ratio of emission of radiant energy by an opaque material to the emission of a perfect emitter, or blackbody, at the same temperature. Emittance, a practical measure of a material's radiant emission, is distinct from emissivity, a

more nearly ideal property obtained by measuring a material whose surface has been carefully prepared to be optically flat.

In applications where heat flow varies with time, the heat capacity of the insulation affects the heating or cooling of the insulation material and must be considered.

A "thermal insulation system" is a combination of materials selected for their chemical, physical, and structural properties. These materials are integrated with the structure to be insulated to obtain the most effective system for specified operating conditions.

FUNCTIONS

A single, homogeneous thermal insulation material cannot withstand all the extreme-temperature conditions encountered by cryogenic vessels or hypersonic-speed aircraft without introducing serious design penalties. Combinations of materials with desired physical, chemical, and mechanical properties are much more effective. These combinations may take the form of discontinuous phase matrices such as: (1) one in which particles, flakes, or fibers are dispersed in varying proportions; (2) a laminate of two or more layers, either bonded together or held loosely in a multilayer sandwich; or (3) a low-density core of a honeycomb or foam material encased by sheets of higher-density materials. Such a composite material can be assembled into a thermal insulation system to provide maximum insulating effectiveness with the desired structural integrity.

The advantage of the system approach to thermal protection is that materials can be chosen on the basis of the most advantageous physical, chemical, and mechanical properties in a specific temperature range to withstand predicted heating conditions. The most effective load-carrying element can be arranged to withstand such outside forces as compressive loads, vibrations, and shocks, and to support an outer structure that excludes the outer environment. The integration of the insulating material and the load-carrying elements of such a thermal insulation system to provide optimum performance under specified conditions requires careful selection of the component materials and care in its design and application.

Structural and environmental variables influence the physical, chemical, and mechanical behavior of the insulation materials and place serious constraints on the types of materials that can be used for a thermal insulation system over a specified range of temperatures. Thus, a material which may have a low thermal conductivity near room temperature may lose all mechanical

strength at elevated temperatures, react with other components of the system, or be uneconomical to produce or difficult to apply. Conversely, an assembly of materials which have been shown in the laboratory to have excellent performance at cryogenic temperatures may not withstand the mechanical shock and vibration of a cryogenic tank designed for over-the-road transport. The end applications of thermal insulation systems must be considered, lest the handling and transportation of the insulated objects prior to final use decrease reliability or increase the complexity of maintenance procedures.

HEAT TRANSFER

Heat can flow through an insulation by the simultaneous action of several different mechanisms:

- Solid conduction through the materials making up the insulation and conduction between individual components of the insulations across areas of contact
- Gas conduction in void spaces contained within the insulation material
- Radiation across these void spaces and through the components of the insulation.

Because these heat-transfer mechanisms operate simultaneously and interact with each other, it is not possible to superimpose the separate mechanisms to obtain an overall thermal conductivity. The thermal conductivity of an insulation is not strictly definable analytically in terms of variables such as temperature, density, and physical properties of the component materials. It is, therefore, useful to refer to an apparent thermal conductivity, which is measured experimentally during steady-state heat transfer and evaluated from the basic Fourier equation:

$$\dot{q} = kA \frac{T_1 - T_2}{L}$$

where:

$\dot{q}$	heat flow through the material
k	apparent thermal conductivity
A	area
T_1, T_2	boundary temperatures
L	thickness of the insulation

The primary effort in the development of more effective thermal insulations is directed toward reducing the different heat-transfer mechanisms. To aid these efforts, the effects of variables —solid conduction, gas conduction, and radiation—on thermal conductivity had to be determined.

Solid Conduction

The contribution of solid conduction can be reduced by breaking up the heat-flow paths within an insulation. This is accomplished by using either finely divided particles or fine fibers so that resistances to heat flow are formed at the surface of each insulation component. In foams, small pore sizes and thin-wall structures are desirable for the same reason. To maintain these circuitous heat-flow paths, the contact area between individual particles or fibers must be reduced to point contacts, whose resistances depend upon the deformation caused by the compressive load imposed on the insulation. These resistances will be enhanced by an increased modulus of elasticity of the components of the insulation and a reduced solid thermal conductivity. Hollow particles or those with a structured interior tend to exhibit a lower thermal conductivity than solid particles. Fine screens separating radiation shields in multilayer insulations, small-diameter powders and fibers, or disks of metal foils dusted with fine powder also exhibit markedly lower thermal conductivity because of increased contact resistance.

Gas Conduction

The low thermal conductivity of evacuated thermal insulations can be largely attributed to the removal of gas from the void spaces within the insulation. The gas itself is a dominant contributor to heat flow through the insulation because it provides good thermal contact between the different components of the insulation. The degree of vacuum necessary to achieve the desired insulating effectiveness can be established by considering the mechanism by which heat flows through a gas bounded by the surfaces of the insulation components. According to the kinetic theory of gases, the thermal conductivity of a gas is proportional to the mean free path of the molecules and the gas density.

The effect of gas conduction can be divided into two separate regions:

● The region ranging from atmospheric pressure down to a few torrs (a torr is equal to one millimeter of mercury), in which gas conduction is independent of pressure

● The region at pressures below a few torrs, in which gas conduction depends on pressure

The transition from one type of gas-conduction region to the other depends upon the dimensions of the individual components of the insulation. For example, the diameter of a particle, the spacing between radiation shields, and the diameter and arrangement of pores determine the pressure required to obtain a mean free path of the gas molecules within a desired gas-conduction region. A decrease in gas pressure results in an increase of the mean free path until the mean free path is of the same order as the distance between insulation components. Further decrease in pressure can no longer influence the mean free path of the gas molecules being constrained by the insulation components. However, the density of the gas is directly proportional to the pressure and will continue to decrease as gas molecules, which then transfer heat directly between adjacent components without suffering collision, are removed.

The larger the voids between the components of the insulation, the lower the pressure required to approach the pressure-dependent gas-conduction region. Because the degree of vacuum required to obtain a high insulating effectiveness in evacuated powder, fiber, or multilayer insulations is difficult to achieve, voids between components of the insulation should be small enough so that gas conduction can be greatly reduced. For example, it is desirable to use a range of sizes of powder insulations so that large voids will be filled by smaller particles and small voids in turn by still smaller particles. In fiber insulations, submicron-sized fibers will, for the same reasons, provide a more effective insulation performance at high gas pressures.

In the pressure-dependent gas-conduction region, the thermal conductivity of the insulation still has a finite value because heat can be transferred by residual gas conduction, by solid conduction within and through the components of the insulation, and by radiation across the voids and through these components. The contribution to the heat flow by gas conduction in an insulation and the mechanisms for transferring heat between adjacent particles have been the subject of many detailed investigations. These investigations have shown that for fine particles up to 0.004 inch in diameter, a reduction in gas pressure to about 10^{-1} torr is sufficient to decrease gas conduction to a negligible value.

Radiation Heat Transfer

Powders and Fibers

Radiation emanating from a warm boundary can pass through powders or fibers and, by absorption within the insulation, heat components by an irreversible process. As the radiation passes through the particles it is partially scattered and absorbed. The transmission of radiation through an absorbing and scattering material is complex. Analyses indicate that the radiation heat-transfer contribution to thermal conductivity is a function of the cube of the temperature and is inversely proportional to the scattering and absorption cross sections. The rate of radiation heat transfer may be changed by absorption, reradiation, and scattering. Absorption is closely related to the physical characteristics of the material itself and is influenced by the wavelength distribution of the incident radiant energy and the emittance of the individual components.

It is possible to select optimum particle sizes for attenuating radiation. The optimum size depends upon the wavelength distribution of the incident radiation. The reduction of the emittance of surfaces enclosing the insulation will further reduce the radiation heat transfer through it. The inclusion of a number of highly reflective thin flakes, or finely divided reflecting materials capable of reradiation, will reduce the radiation heat transfer. The addition of absorbing material in the form of fine powders such as carbon will tend to further attenuate the radiation heat transfer through an insulation.

Multilayer Insulations

In multilayer insulations, the principles used to obtain more effective evacuated powder and fiber insulations were carried to a logical conclusion by the recognition of the importance of radiation heat transfer once the mechanisms of gas conduction and solid conduction have been reduced. In this insulation, radiation shields of the lowest emittance are separated by spaces of very low conductivity exposed to a high vacuum. In an idealized assembly of radiation shields (i.e., where the radiation shield is defined as an isothermal surface of low emittance having no direct contact with adjoining surfaces and/or boundaries), radiation heat transfer is directly proportional to the emittance of the surfaces and inversely proportional to the number of radiation shields between the two temperature boundaries. In practical multilayer insulations, radiation heat transfer between two ra-

diation shields with an intervening medium of an optically non-transparent spacer involves complex interactions between the reflective properties of the radiation shield and the absorption and scattering properties of the spacer.

LABORATORY MEASUREMENT TECHNIQUES

Because of the complexity of the heat-transfer phenomena that control the performance of thermal insulations, data obtained from laboratory tests are essential in developing insulations and in guiding their installation. Although considerable data have been accumulated on insulation performance under different conditions, a specific application may differ to such an extent that extrapolation of the available data can provide only an estimate, rather than a firm prediction, of insulation performance.

The efforts devoted to establishing suitable test methods and procedures to provide the desired data indicate the importance of laboratory tests. Although at present only a few thermal conductivity test methods are standard (for example, the ASTM guarded-hot-plate method), efforts are being made to standardize them, particularly in the range of cryogenic temperatures. Methods developed in response to the need for accurately predicting thermal properties of insulation exposed to extremes of environment are discussed in the following text.

Density

Normally, in the literature, the reported density for a thermal insulation corresponds to room-temperature conditions. If the thermal coefficient of expansion for the insulation is known, the density can be corrected to correspond to any particular set of operating temperatures. The thermal coefficient of expansion is generally reported for solid and foam insulations, but no such data are found in the literature for powder, fiber, and multilayer insulations.

The volume of a sample of rigid insulation material can be determined by measuring the volume of water it displaces. The volume of an insulation such as a closed-cell foam can be determined by measuring and multiplying its length, width, and height together. However, the densities of powder, fiber, or multilayer insulations that are subject to compression and are affected by shock and vibration cannot be measured by this method.

Reference 7 suggests a method for measuring the volume of fibrous or multilayer materials by placing a sample of known

diameter (or length and width) between two parallel plates. The distance between the plates is assumed to be the average thickness of the sample when both plates are touching the sample at least in a few places. From that position the plates can be brought closer only by the application of a compressing force to the sample. The distance between the plates is plotted against the compressive load applied to the sample. Assuming that the diameter of the sample remains constant throughout the compression cycle, the volume and the density of the sample can be expressed as a function of the applied compressive load.

Because it is difficult to define the density of powder, fiber, or multilayer insulations, the weight of insulation covering 1 square foot of area is often used. To describe the insulation further, the nominal thickness of the layer or the number of radiation shields of a multilayer insulation are reported.

Specific Heat

Traditional experimental methods are used to measure the specific heat of insulation materials. The specific heat of foam, powder, fiber, and multilayer insulations is estimated by summing the weighted heat capacities of the constituent materials and dividing by the sample weight.

Thermal Conductivity and Thermal Diffusivity

Because of the very low thermal conductivity of effective cryogenic insulations and the difficulty in obtaining low temperatures, unique thermal conductivity apparatus capable of measuring small heat flows through test materials had to be developed. Each investigator tended to design and develop his own test apparatus for a specific material and for the variables he planned to investigate. Several designs for thermal conductivity test apparatus have evolved, although none of them can be called standard. Nor is any one capable of meeting all the required test conditions. Most of the designs presently in use are classified by the shape of the sample test chamber: spherical, cylindrical, and flat plate.

Spherical Apparatus

An apparatus of this kind is shown in figure 6. It consists of an inner spherical shell containing a cryogenic liquid and an outer spherical shell kept at a uniform temperature by an electrical heater or circulating liquid. The test sample is placed between the two shells. The boiloff rate of the cryogenic liquid is an
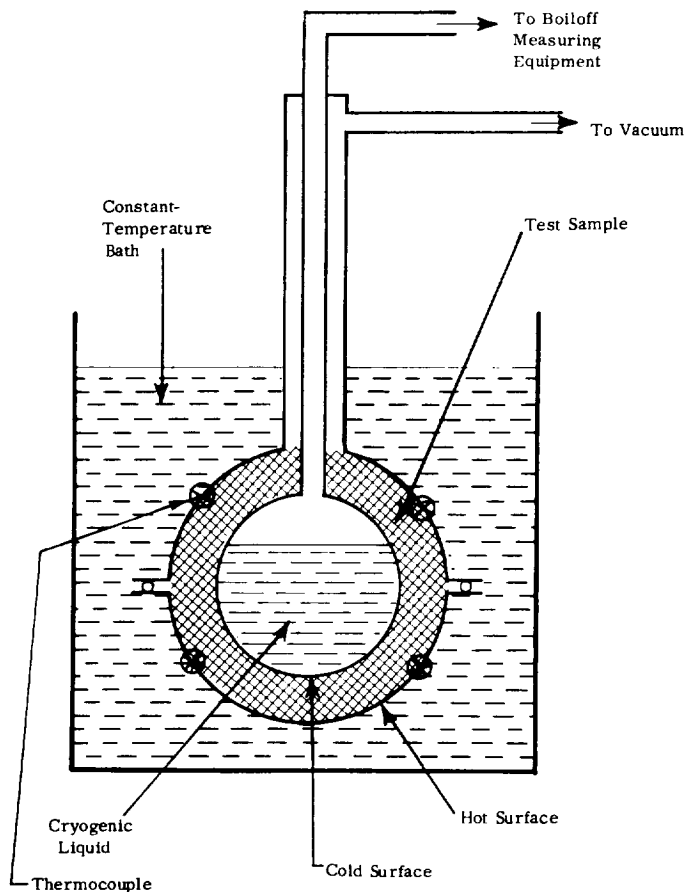
FIGURE 6.—Spherical thermal conductivity apparatus.

indication of the heat flow through the material and is used to calculate the thermal conductivity (ref. 8). Figure 7 shows a variation of the spherical type of apparatus, in which an electrical heater is installed inside the inner shell and the outer shell is immersed in a cryogenic liquid. In this case, the heat input of the heater is used to calculate the thermal conductivity.

The advantage of the spherical apparatus is its simplicity of construction. However, it has several disadvantages:

● A spherically shaped insulation sample is difficult to produce, except for materials such as powders, fibers, and some foams.
● The uniformity of the sample cannot be easily controlled.
● For each size of the sample a separate set of shells must be provided.
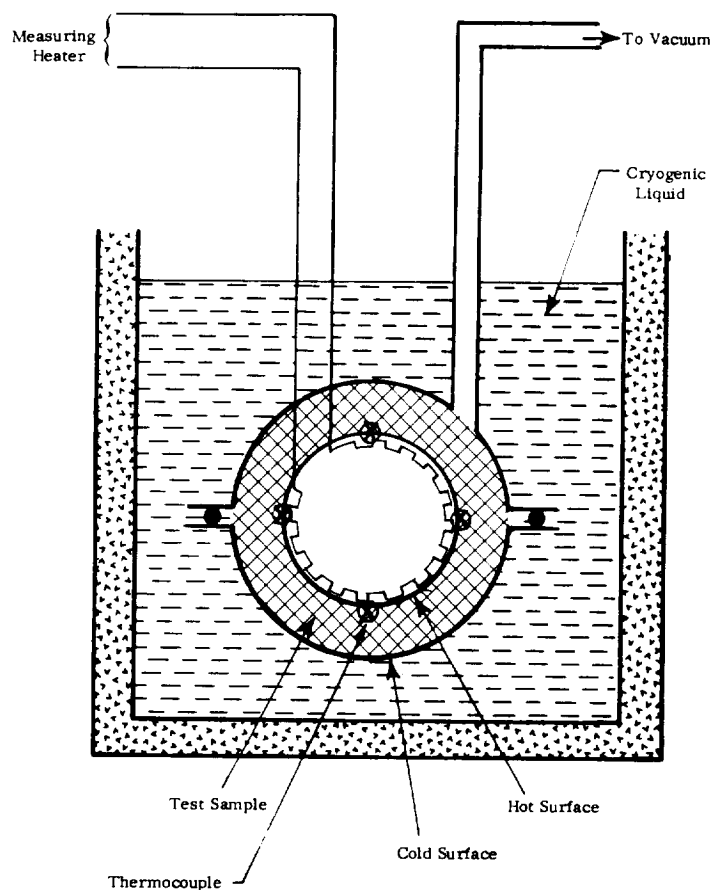
FIGURE 7.—Spherical thermal conductivity apparatus with electrically heated core.

● It is difficult to apply compressive loads to the sample.
● The heat leak along the neck of the spherical apparatus cannot be accurately estimated.

Cylindrical Apparatus

Figure 8 shows a cylindrical thermal conductivity test apparatus (ref. 9). It consists of a cylindrical measuring vessel guarded on both ends by cylindrical guard vessels. The upper guard vessel also reduces the heat loss through the neck of the measuring vessel. All three vessels are filled with the same cryogenic liquid. The outer jacket is kept at a uniform temperature by an electrical heater or constant-temperature liquid bath. The
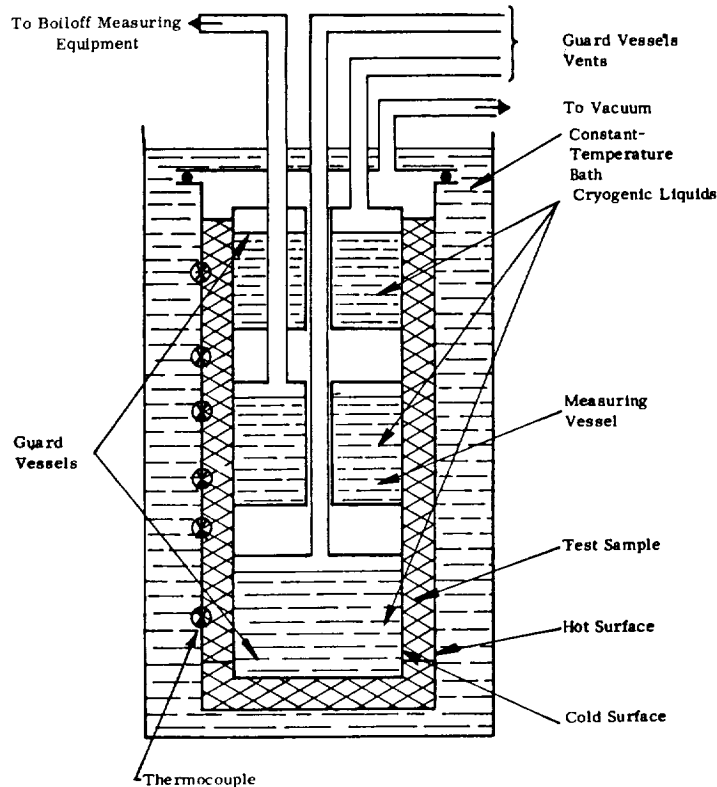
FIGURE 8.—Cylindrical thermal conductivity apparatus.

boiloff rate of the cryogenic liquid in the measuring vessel is used to calculate the thermal conductivity of the sample.

This apparatus is adaptable for testing powder, fiber, and multilayer insulations, but, like the spherical type, it is not easily adaptable for investigating the effects of density changes due to compression of the sample. However, this type of apparatus has found wide application, primarily where simplicity of design and low cost are required and the variables to be measured are few.

Flat-Plate Apparatus

The flat-plate thermal conductivity test apparatus consists of hot and cold flat plates, between which a flat sample can be inserted. This concept approaches that of the standard guarded hot plate (ref. 10) and has been shown to be versatile. Several approaches can be used in designing the apparatus.

Guarded-hot-plate apparatus

Figure 9 shows a single-guarded-hot-plate apparatus. It consists of a cold plate, uniformly cooled by a cryogenic liquid, and an electrically heated hot plate surrounded by a guard ring. The temperature of the guard ring is kept equal to that of the measuring hot plate to prevent heat transfer between the guard and the measuring plates. The electrical heat input into the measuring hot plate is assumed to be equal to the heat flow through the sample. Such an apparatus was used to investigate the influence of compressive loads, sample thickness, density, and operating temperature on the thermal conductivity of powders and fibers in a vacuum. Some difficulty was experienced in maintaining equal temperatures in the heated guard and measuring plates. This problem tends to be accentuated when materials of higher insulating effectiveness are tested, unless a sensitive control circuit is used.

Banjo-type guarded-hot-plate apparatus

Figure 10 shows a banjo-type guarded-hot-plate apparatus (ref. 11). It has an electrically heated hot plate inside a ring-shaped guard heater. Two flat test samples are placed on each
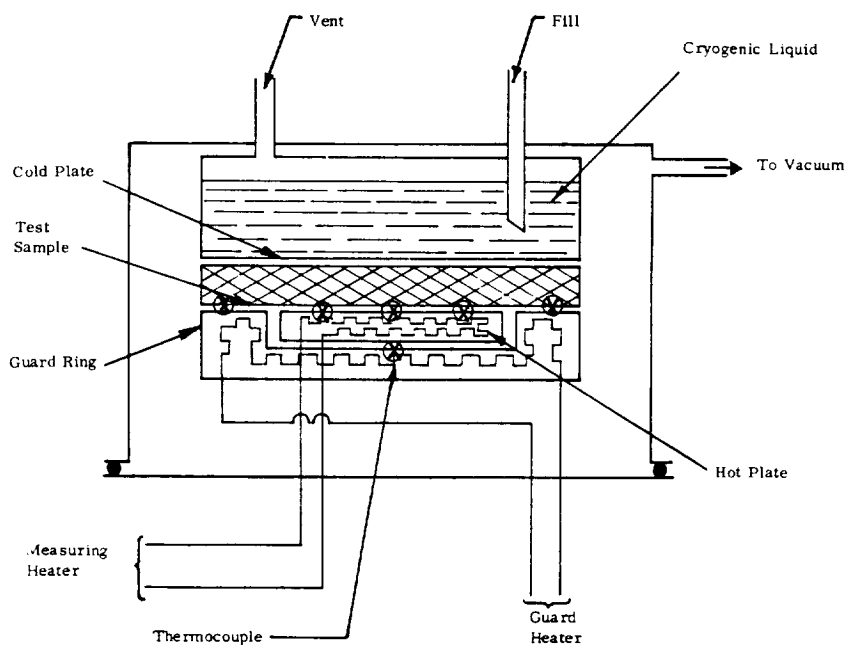
FIGURE 9.—Single-guarded-hot-plate thermal conductivity apparatus.
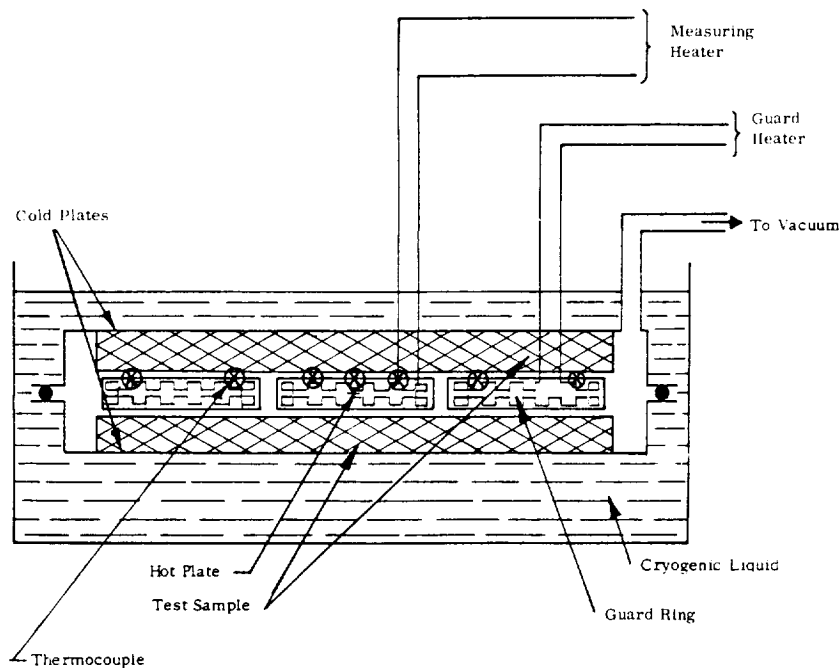
FIGURE 10.—Banjo-type guarded-hot-plate thermal conductivity apparatus.

side of the hot plate. The complete assembly is enclosed in a container that can be evacuated and immersed in a constant-temperature bath. This apparatus permits the measurement of thermal conductivity over a range of temperatures. However, the physical environment of the sample tends to be harder to control. This apparatus has been useful for measuring foamed materials at cryogenic temperatures and has provided data required for launch vehicle thermal protection systems.

Guarded-cold-plate apparatus

Figure 11 shows the single-guarded-cold-plate apparatus (ref. 12). Its design is a modification of the Wilkes calorimeter (ref. 13). In the single-guarded-cold-plate apparatus the bottom of the measuring vessel constitutes the cold plate. The 3-inch-diameter measuring vessel is surrounded by a 6-inch-diameter guard vessel. The hot plate is kept at a uniform temperature by a circulating fluid. The boiloff rate of the cryogenic liquid in the measuring vessel is recorded and is used to calculate the heat flux through the insulation sample. An improved version of the apparatus (fig. 12) was designed recently (ref. 14).
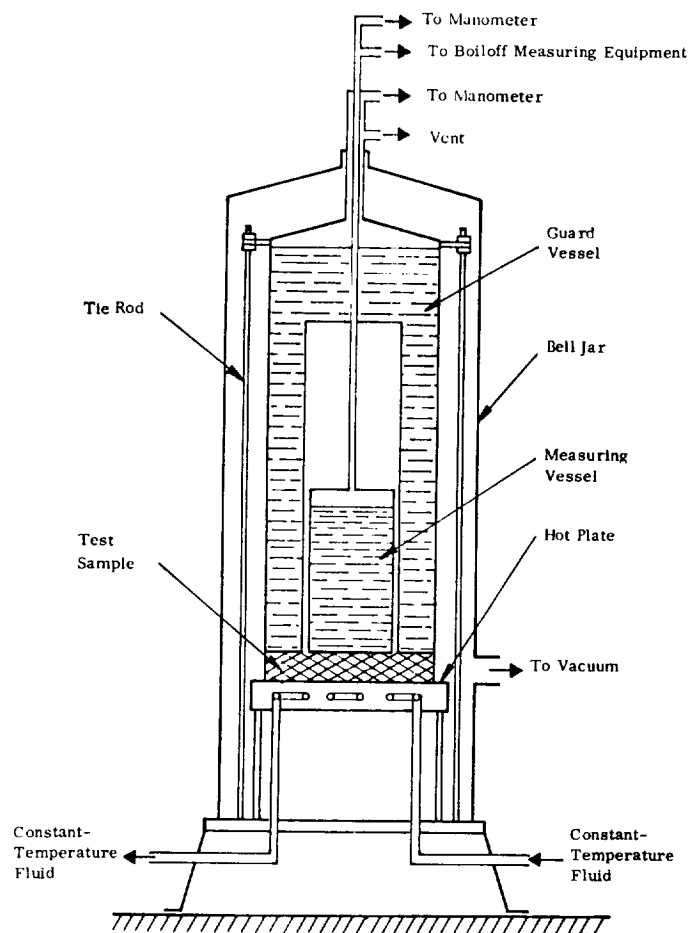
FIGURE 11.—Single-guarded-cold-plate thermal conductivity
apparatus.

The double-guarded-cold-plate apparatus can measure the ther-
mal conductivity of disk-shaped samples of multilayer, powder,
fiber, and cellular insulations of organic and inorganic materials
with a thermal conductivity as low as 0.14 mW/cm¹-°C¹
(1×10^{-4} Btu-in./hr-°F-ft²).

Depending upon the boiling point of the specific fluid used, one
side of the sample can be exposed to a range of discrete temper-
atures from $-423°$ to $-23°$ F (20° to 243° K). By proper choice
of fluids and automatic temperature control, the other side of
the sample can be exposed to a range of temperatures from $-320°$
to 440° F (77° to 500° K). The test-sample disk can range in
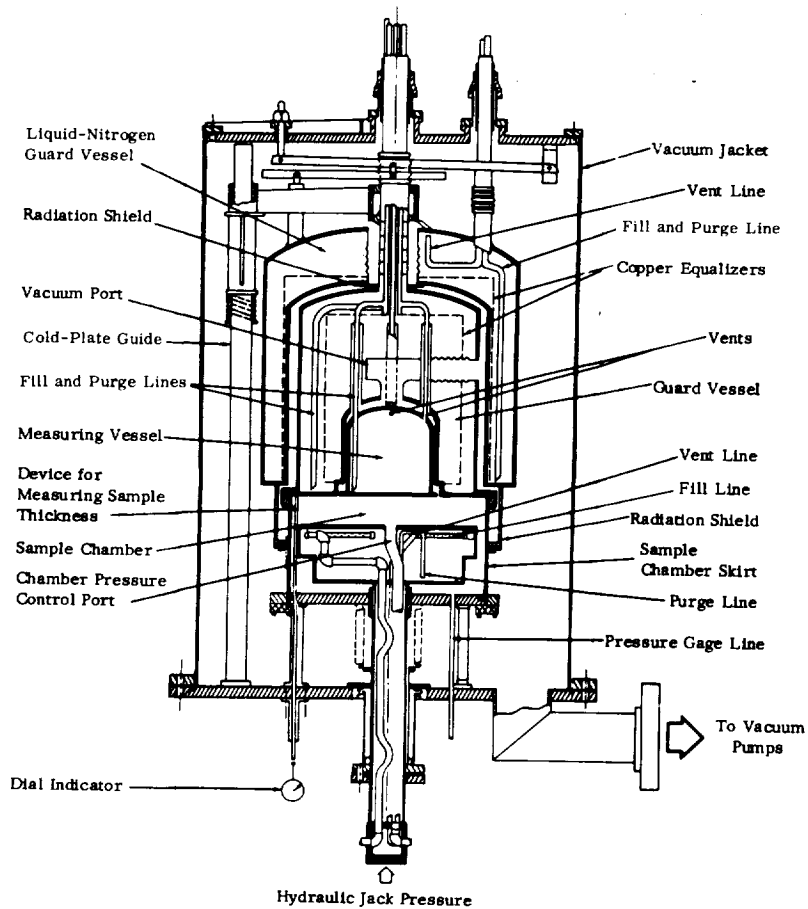
FIGURE 12.—Cross section of double-guarded-cold-plate thermal conductivity apparatus.

thickness from 0 to 2 inches with diameters of up to 12 inches. The diameter of the measuring section of the sample is 6 inches. The sample can be exposed to any desired gas at pressures from 10^{-6} torr up to 14.7 psia. Additionally, the test chamber can be purged with gases at controlled pressures. The test-sample thickness can be changed during a test by moving a hydraulically actuated hot plate. Parallel alinement of the hot and cold plates and the thickness of the test sample can be measured during the test with an accuracy of 0.001 inch (25 microns) by three dial indicators. While the test is in progress, compression loads from 0 to 22 psi can be applied to the sample by a hydraulically controlled and calibrated pressure unit. During the test, the edges

of the sample can be exposed to temperatures ranging from
−320° to 440° F (77° to 500° K) by means of a guard shield.

Flat plate with heat meter

This apparatus consists of two copper plates (½ inch thick by
12 inches square in the apparatus described in ref. 15). One plate
is maintained at −315° F (80° K) by liquid nitrogen, the other
near ambient temperature by circulating water. A heat-flow-
meter assembly consists of a 4-inch-square thin plastic plate with
a thermocouple pile surrounded by a ring-shaped plastic square
of the same thickness. The assembly is cemented to the warm
plate. The heat-flow meter is factory calibrated or can be cali-
brated with a sample of known thermal conductivity. (The ap-
paratus described in ref. 15 has vertical cold and warm plates.)

Transient-Heat-Flow Measurement Method

The devices previously discussed are based on measurement of
a steady-state heat flow. Several instruments are available which
can measure thermal diffusivity during the period of transient
heat transfer. Given the density and specific heat, thermal con-
ductivity of the material can be calculated from this measure-
ment.

The transient-heat-flow measurement method is faster than
the steady-state heat-flow measurement method but less accurate.

Line heat source apparatus

The line heat source apparatus is designed to measure thermal
conductivity of powders at low pressures (10⁻¹⁰ torr) and low
temperatures (ref. 16). The apparatus consists of a heater wire
and a parallel thermocouple wire, suspended on a support struc-
ture inside a sample holder as shown in fig. 13. The support
structure for the heater and thermocouple wires consists of a
stainless-steel base 1 inch wide by 6 inches long by ⅛ inch thick.
Four stainless-steel supports (two on each end of the base) have
been attached with epoxy resin to ⅟₁₆-inch holes drilled in the
stainless-steel base. Similarly, four ceramic-to-metal insulating
binding ports (two on each end of the base) are attached to the
steel base approximately ½ inch from the stainless-steel supports.

A 0.001-inch-diameter constantan heater wire is attached with
epoxy resin to one pair of stainless-steel supports. The epoxy
resin electrically insulates the heater wire from the stainless-
steel supports. The wire is firmly attached to be taut without
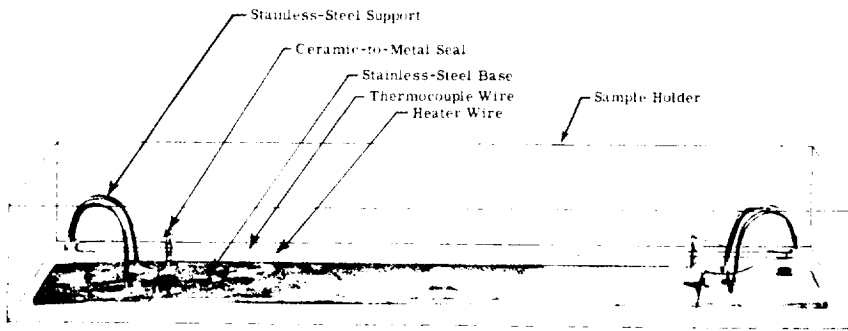
FIGURE 13.—Line heat source apparatus.

undue strain. The wire continues from the stainless-steel supports and is soldered to the nearest ceramic-to-metal binding posts. The total heater-wire length is 8 inches, the supported length is approximately 5-½ inches, and each end loop (between the supports and the binding posts) is approximately 1-⅛ inches long. A 0.001-inch-diameter iron-constantan thermocouple is parallel to, and approximately ³⁄₆₄ inch from, the heater wire and is supported by the second set of supports and binding posts. Both wires are approximately ¼ inch above the steel base. The end loops of the thermocouple wires are approximately 1-⅛ inches long; the wire length between the stainless-steel supports is approximately 5-½ inches. The iron-constantan thermocouple junction is made by placing the two wires next to each other, silver-soldering the junction, and trimming off the excess wire. Heater wire leads of 0.015-inch stranded copper wire, approximately 18 inches long, are attached to two binding posts. Heavier No. 36 thermocouple lead wires, 36 inches long, are attached to the other two binding posts. The resistance of the lead wires is less than 1 percent of the total resistance. An iron-constantan thermocouple reduces axial heat losses (iron has a thermal conductivity less than one-sixth that of copper). Although the wires are positioned firmly, they are quite fragile.

The sample holder for the line heat source is machined from a copper block; holes are bored along the walls and base for cooling passages. A cooling or heating fluid can be passed through the walls and base of the holder to bring the samples to the desired temperature.

Thermal conductivity probe apparatus

A thermal conductivity probe is shown schematically in figure 14 (ref. 16). This device is more rugged than the line heat
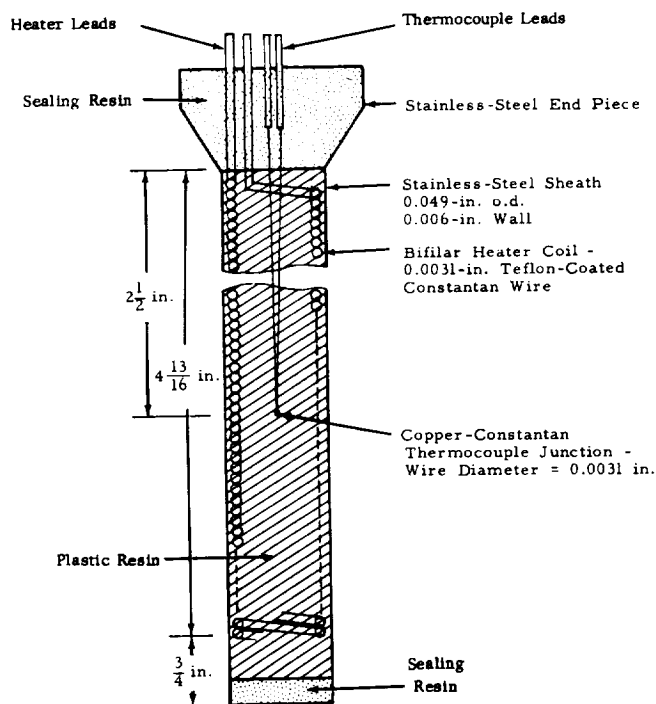
FIGURE 14.—Thermal conductivity probe apparatus.

source apparatus and is particularly useful as a quality control tool for foam, fibers, or powders. A bifilar coil is wound with fluorocarbon-coated constantan wire. A fluorocarbon-coated copper-constantan thermocouple (welded joint) is inserted at the midpoint of the coil. The probe is filled with a plastic resin. The outer sheath of the probe is type 304 stainless steel. The top of the probe consists of a cone-shaped holder in which the smaller heater wires are connected to copper leads. The thermocouple leads are continuous for several feet. The bottom and top of the probe are filled with a sealing resin. Filling the probe with a plastic resin prevents possible outgassing due to leaks in the probe sheath and therefore eliminates the possibility of internal contact resistances within the probe.

The probe sample holder (fig. 15) consists of a copper sheet formed into a cylinder 4-3/4-inch i.d. and 6-5/8 inches high. Quarter inch copper tubing is soldered to the wall and to the bottom of the sample container; legs are provided to maintain clearance between the bottom of the sample container and the base plate. A copper lid can be attached to the holder by wing nuts.
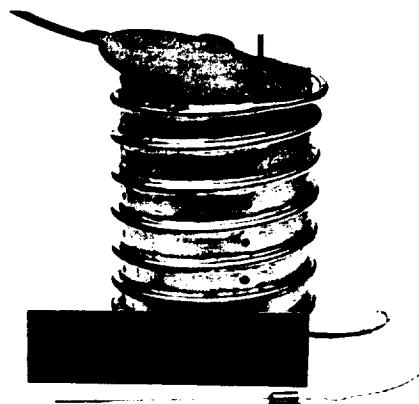
FIGURE 15.—Thermal conductivity probe and sample holder.

Non-steady-state thermal-conductivity tester

This device is illustrated in figure 16 (ref. 17). A high-conductivity mass and the insulation are initially at the same constant temperature. They are suddenly exposed to a low temperature, and the outer boundary of the insulation cools rapidly to a new temperature. The high-conductivity mass, however, isolated from this new boundary temperature by the insulation, will at first undergo no temperature change but will eventually begin to cool and will ultimately approach the temperature surrounding the tester. The rate at which the mass cools is governed by the weight and heat capacity of the mass itself as well as by the weight, heat capacity, and thermal conductivity of the surrounding insulation.

Two models of this tester have been developed: one for powder insulations and the other for multilayer insulations. Both can measure the performance of insulations in a vacuum environment. The major difference between the two models is the size of the thermal mass. Since multilayer insulations are nonisotropic, physical configurations are significant. A compromise has to be made between a tester small enough for easy use and an ideal (i.e., infinitely long) cylinder with no end-heat loss. By extending the insulation around the ends of the cylinder, the end-heat loss is minimized and approaches that of the cylindrical-surface loss per unit area.

The temperature of the insulated body is monitored by chromel-constantan thermocouples anchored to the vessel and passing through the insulation and the outer vacuum jacket. The testers are heated and cooled within a large-mouth Dewar. Heating is
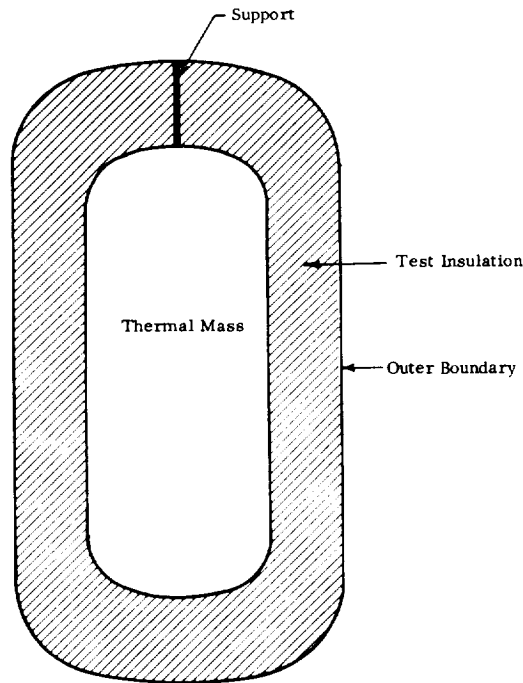
FIGURE 16.—Non-steady-state thermal conductivity tester.

accomplished with an immersion heater controlled by a bulk-type thermostat. Liquid nitrogen is used for cooling.

PROTOTYPE TESTS

New thermal insulations should initially be evaluated in a thermal conductivity apparatus. Before an insulation system can be judged suitable, however, it should be thoroughly tested in a simulated operational environment. This usually requires that a prototype tank be constructed, insulated, and tested under various controlled conditions. In progressing from laboratory thermal conductivity tests to prototype tests—and subsequently to full-scale tests—a logical sequence of steps in the development of new insulations can be maintained.

Most space-oriented programs have been concerned with protecting and insulating liquid-hydrogen tanks, but the test methods and the results obtained are applicable to the storage of any cryogenic fluid in terrestrial environments.

An environmental chamber is designed to simulate the conditions to be encountered by the thermal insulation system during

operation. Because of the variety of factors to be considered, it is easier to simulate each condition imposed on the insulation separately. Descriptions of the various types of environmental simulation chambers which have been used to test insulation system concepts on prototype or full-scale tanks are given in the following text.

Simulation of Operational Environments

Terrestrial Simulation

For these tests, insulated tanks are placed inside a chamber in a convenient, safe location and exposed to controlled wind, rain, humidity, and temperature conditions. A well-designed insulation system should be independent of these weather conditions. One test chamber was constructed to maintain a dry nitrogen atmosphere around the tank. The temperature in the chamber was controlled with steam coils (ref. 18). If the insulated tank is to be road transportable, tests to establish the effects of vibration and shock are carried out in a separate facility.

Rocket-Launch Simulation

Typical launch simulation includes:

● A rise in temperature of the surface of an exposed tank as a result of the high velocity attained in the atmosphere
● A dynamic pressure transmitted to the insulation
● A rapid decrease in ambient pressure as the rocket gains altitude

A typical profile of a launch trajectory is shown in figure 17. The dynamic pressure builds up to a maximum of about 900 psf before the surface temperature changes significantly. At higher velocities (i.e., mach numbers), the temperature increases to a maximum of nearly 700° F (370° C) before it decreases. Typical pressure-temperature curves are shown in figure 18. The temperature peak and rapid pressure decay are clearly indicated. Environmental launch simulation must reflect such changes.

Noise simulation in the range of 153 to 158 decibels is a part of prototype tests, although it is usually carried out in a separate test facility (ref. 18).

Space Simulation

At the end of the powered phase of flight, the tank is in a near-zero-gravity field. If the cryogenic fluid is to be stored for
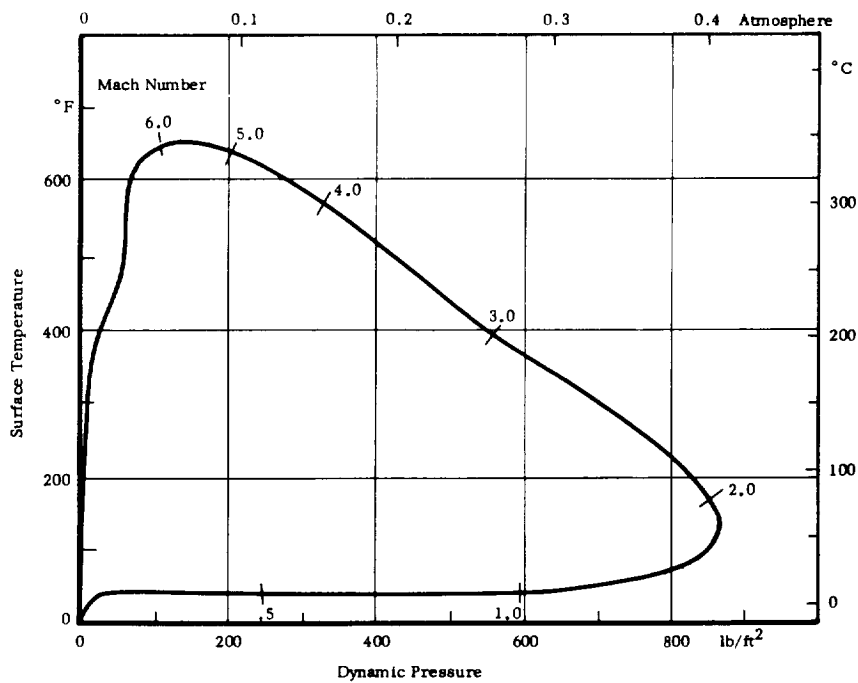
FIGURE 17.—Dynamic pressure versus surface temperature: typical launch-trajectory profile.
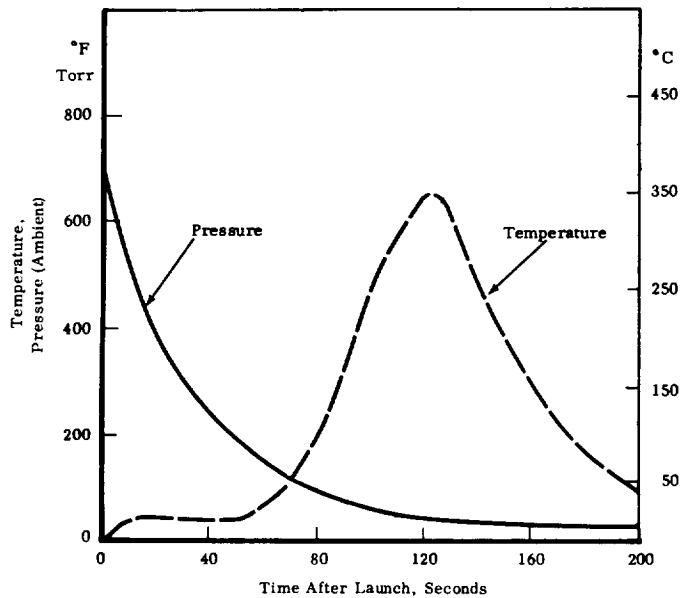
FIGURE 18.—Typical pressure-temperature curves in rocket-launch simulation.

later use, then the storage tank must be insulated against heat leaks for days or perhaps even months.

In space, the primary purpose of the insulation is to prevent solar and planetary thermal radiation from penetrating to the tanks. At the Earth's distance from the Sun, the solar heat flux is about 430 to 440 Btu/hr-ft² (0.136 to 0.140 W/cm²) (refs. 19, 20). This value varies inversely as the square of the distance from the Sun. The Sun can be approximated by a blackbody with a temperature near 10 000° F (5500° C), although radiation levels at wavelengths less than 0.25 micron and greater than 2 microns are not well known. In addition, there may be planetary radiation to simulate. For example, 100 miles above Earth, a radiation level of about 234 Btu/hr-ft² (0.074 W/cm²) is experienced on the projected area (ref. 21). This radiation can be simulated by a source at about 10° F (−12° C) with an emissivity of 0.6. Because the solar or planetary radiations are directional, the thermal radiation impinging on the tank should be parallel rays emanating from a suitable radiation source. Different tank orientations within a chamber will expose the tank to different heat fluxes.

In addition to simulating thermal radiation, the pressure in the environmental chamber must simulate space or planetary conditions. Other environmental factors such as micrometeoroids and particulate or ionizing radiation from a nuclear propulsion system, or the Van Allen belts (refs. 20, 22), are not simulated in the chamber, although the materials considered for an insulation system should be tested in these environments. Heat leaks due to supports or piping leading from the tank to other portions of a space vehicle can be simulated by adjusting both the position of the tank in the chamber well and the support method so that the combined effect of the two achieves the desired heat loss.

Environment-Simulation Chambers

Ground or Prelaunch Tests

Tests of large insulated liquid-hydrogen tanks in a prelaunch environment have been carried out in convenient and safe locations. A number of such tests have been made and the heat leak measured by monitoring the vent flow gas (refs. 24–27).

Launch Tests

Such tests are carried out in a combustion gas flow tunnel. In one set of experiments, only the temperature and dynamic

pressure effects were studied (ref. 25). A tank containing liquid nitrogen was covered with various insulation panels and placed in the tunnel. The time to attain peak air temperature was varied between 10 and 20 seconds. Temperatures of up to 900° F (480° C) were attained with a corresponding dynamic pressure of 13 psi. After each test the degradation of the insulation was determined.

In a more complete test of a prototype tank, subsonic tests were first carried out by placing the insulated tank at various distances behind the exhaust of a turbojet engine (ref. 26). A wide range of dynamic pressures and gas temperatures was employed. To test the systems in the transonic and supersonic range, the tank was located in an 8- by 10-foot supersonic wind tunnel fed with hot combustion gas. The tank was filled with liquid nitrogen and air velocities varied from Mach 0.5 to 2. The angle of attack was 0°. In some tests a 15° wedge or blunt body was mounted on the top of the tank to induce standing shock waves. Figure 19 shows the experimental setup.

In these tests the rapid decrease in static pressure was not simulated. The insulated tank was placed in a chamber which was subsequently evacuated to simulate the pressure-time history of the launch.
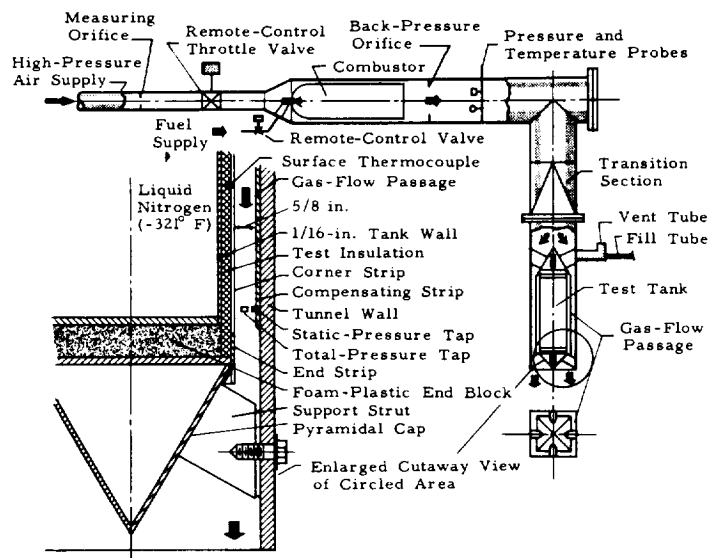
FIGURE 19.—Prototype tank test setup.

Space-Flight Tests

A number of insulation systems have been tested in low-pressure chambers (refs. 19, 28, 29). A typical test chamber is shown in figure 20. The double vacuum chamber allows an accurate measurement of heat leaks and assures good vacuum seals at low temperatures. A similar apparatus has been used to test insulation panels for a liquid-hydrogen tank (ref. 26). These panels are made with a full-scale curvature of 60 inches. They are first placed in the chamber at ambient conditions. The pressure is rapidly decreased and, simultaneously, the insulation is heated with a bank of infrared lamps. Thus launch simulation without dynamic pressures or vibrations is achieved.

The effects of different heat fluxes reaching an insulated tank calorimeter filled with either liquid hydrogen or liquid nitrogen were measured by placing the tank inside an outer vessel which was subsequently evacuated to a low pressure (ref. 30). The heat leak through the insulation was measured after the tank was exposed to different temperatures. The temperatures were varied by using baffles wound externally with tubes so that the upper and lower baffles, at different temperatures, provided a
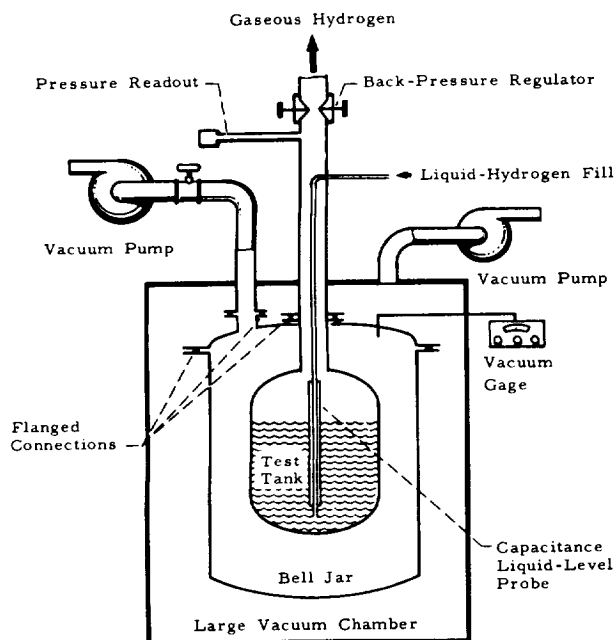
FIGURE 20.—Low-pressure liquid-hydrogen test chamber.

directional heat flux over the top and bottom of the cryogenic tank. Figure 21 shows a chamber with two baffles. The temperatures of either baffle could be varied from liquid-hydrogen temperatures, $-423°$ to $100°$ F ($-253°$ to $40°$ C). The lower temperatures simulate environment of that portion of the tank which radiates to space while the higher temperatures approximate radiation from planets and the Sun.
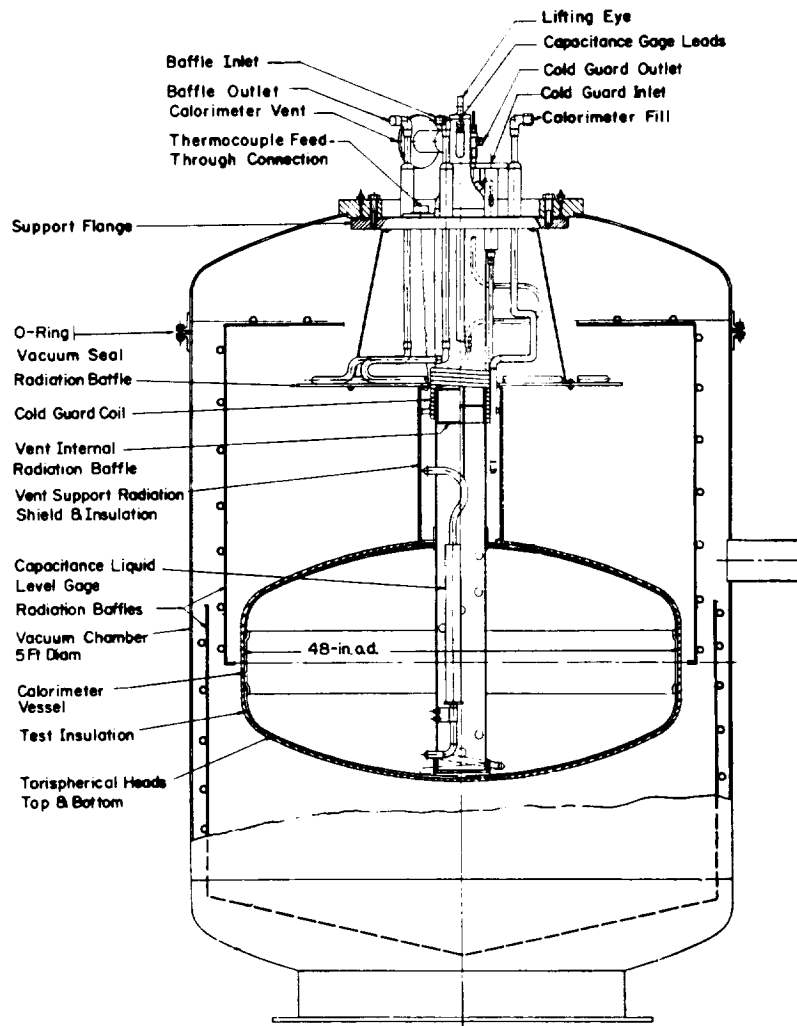
FIGURE 21.—Chamber with two baffles.

Cryogenic Insulation Systems

PLACEMENT OF INSULATION SYSTEMS

Insulations used in spacecraft must withstand a variety of environmental conditions, ranging from those during ground hold through launch to space flight. To meet these conditions several insulation-placement techniques have been developed.

External Insulation

External insulation has been used for the liquid-hydrogen storage tanks of large boosters such as the Saturn S–II and S–IV and for many smaller cryogenic-fluid storage vessels developed for the Apollo program. External insulation is the most widely used because—

- Complex tank shapes can be insulated.
- Insulation thickness can be built up in successive layers or in individual sections.
- Insulation can be integrated with supports and pipes.
- Sections of insulation can be more easily repaired.

External insulation requires that either an outer shell or a vapor-tight barrier be placed over it. After this process has been completed, however, the tank is quite fragile and must be handled with care to prevent damage to the insulation.

Internal Insulation

In this technique, which is applicable primarily to large tanks, the insulation is placed inside the tank shell. The major advantages of such placement are—

- The insulation does not need to withstand aerodynamic heating and pressures during vehicle launch.
- Mechanical handling of the complete cryogenic tank is simpler than that of a tank with a fragile external insulation.
- The insulation is not penetrated by external lines and projections.

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The disadvantages of internal insulation are—

● The insulation must be attached securely to the inner wall and the cryogenic liquid must be prevented (by a vapor barrier) from leaking into the insulation. If such leakage occurs, the liquid will vaporize at, or near, the warm wall and drastically reduce the insulation's effectiveness.

● Defective portions of the insulation are hard to locate and repairs are difficult to make.

● Any separation of the insulation from the wall caused by thermal contraction, vibration, or sloshing will result in an increased heat leak; loose sections of the insulation can plug the liquid supply lines.

Jettisonable Insulation

An alternative, applicable to large space-vehicle cryogenic-fluid storage tanks, is to jettison the insulation after launch. In this case, the insulation is effective only during ground hold and for that time period during launch when high external pressures (dynamic) and temperatures are experienced. Jettisoning the insulation prevents heat absorbed by the insulation during launch from being transferred to the tank. The insulation is held in place mechanically and is not bonded to the tank wall with adhesive. To prevent air condensation, the space between the insulation and the tank wall must be purged with helium.

MATERIALS FOR INSULATION SYSTEMS

Insulations can be categorized according to the form of the materials, such as: loose fill (e.g., bubbles, fibers, flakes, granules, and powders), flexible (e.g., batting, blanket, felt, and multilayer), rigid (e.g., block, board, brick, honeycomb; and molded, foamed, or sprayed-in-place materials). In addition to design criteria and economic considerations, the choice of insulation materials is usually dictated by the operating temperature range.

As shown in figure 22, the weight of insulation materials that are to be used in space-flight applications must also be optimized (ref. 31). For these applications, flexible materials are typically employed. Loose-fill materials, either evacuated or at atmospheric pressure, are employed for storage, transportation, or transfer of cryogenic fluids. Rigid insulation materials are used for both space-flight and terrestrial applications requiring mechanical strength.
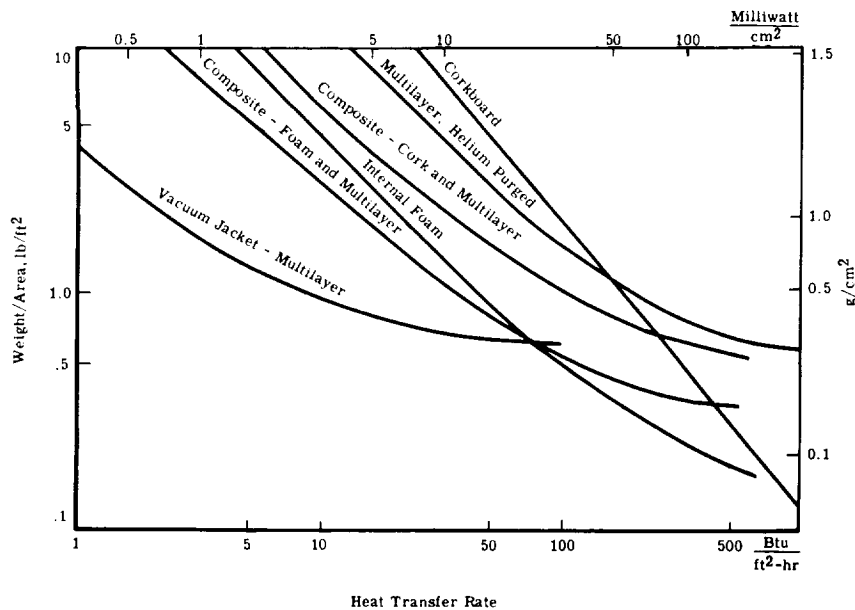
FIGURE 22.—Weight effectiveness of insulations.

Comprehensive literature is available on insulation materials in all of the above categories. The materials that have the most direct application to cryogenic insulation systems and those that are new (i.e., in terms of the type of material, combination of materials, or performance data obtained) are discussed in the following text.

Multilayer Insulations

A multilayer insulation consists of many layers of alternate radiation-reflecting shields separated by low-conductivity spacers. This assembly is placed perpendicular to the flow of heat. Each layer contains a thin, low-emissivity radiation shield enabling the layer to reflect a large percentage of the radiation it receives from a warmer surface. The radiation shields are separated from each other to reduce the heat transferred from shield to shield by solid conduction. The gas in the space between the shields is removed to decrease the conduction by gas molecules. Each component of the insulation is designed specifically to perform a particular function:

- Radiation shields—to attenuate radiation
- Spacers—to decrease solid conduction
- Evacuation—to decrease gas conduction

When the designer selects materials for multilayer insulation, he endeavors to reduce each of the three possible heat-transfer modes. Technological advances resulting in more effective radiation-shield materials, low-conductivity spacers, and improved gas-removal methods promise to improve still further the performance of multilayer insulations.

Spacers

Multilayer insulations can be classified according to the type of spacers separating the radiation shields. Four kinds of spacers are discussed below: multiple resistance, point contact, single component, and composite.

Multiple-resistance spacers

Two surfaces in contact, when not forced against each other, present a relatively high resistance to heat flow at the points of contact. Therefore, a material such as a fibrous mat arranged with fibers in a parallel array, in which the heat must pass from fiber to fiber to reach the next radiation shield, is an effective spacer (ref. 32). The finer the fibers, the greater the resistance per unit thickness the mat presents to the heat flow. Any fibers that are not in the plane perpendicular to the heat flow will act as thermal shorts across the mat.

Glass fibers (as used in glass wool or glass paper), quartz fibers and plastic fibers (polyester mats and others) are being used as spacers in multilayer insulations. Fibrous mats are produced in various thicknesses ranging from 0.003 to 0.030 inch (75 to 750 microns). Fiber diameters range from 0.5 micron (2×10^{-5} inch) to several hundred microns.

The thermal performance of mats with fibers not bonded to each other is better than that of mats with bonded fibers, in which heat can flow across the bonded contact areas. However, the tensile strength of unbonded fiber mats is limited, and they are more difficult to handle. Fibers are either partially bonded or stitched to make the mat, thus increasing its tensile strength without greatly decreasing its thermal performance.

Point-contact spacers

Another method of separating neighboring radiation shields is to place particles along the surface of the shields. If the typical dimension of the individual particle is small compared to the

distance between two particles along the shield, then the contacts between the shields can be considered to be point contacts. The concept is illustrated in figure 23 (ref. 3). In figure 23(a), small spheres are placed between the shields. The distance from sphere to sphere is selected to be a maximum, with the upper limit determined by sagging of the shields that causes direct contact between the shields. In figure 23(b), point contacts between neighboring radiation shields are provided by embossing the spacer material.

Unattached spheres are impractical because the spheres will not maintain their positions. A grid of spheres may be approximated by a screen (fig. 23(c)), whose crossover points (knots) are spheres formed of a thread that is only half the thickness of the knot and that does not contact both radiation shields but keeps the spheres in position. Several insulations have been developed using screens made of nylon, silk, and vinyl-coated fiber glass as spacers. The thickness of the screens ranges from 0.003 to 0.025 inch (75 to 600 microns). Screen mesh sizes ranging from $\frac{1}{16}$ to $\frac{1}{4}$ inch have been investigated. Screens are dimensionally stable spacer material with tensile strength sufficient to simplify application. An additional benefit is derived from the open structure of a screen; that is, the evacuation of gas from a multilayer insulation with a screen spacer is greatly eased.
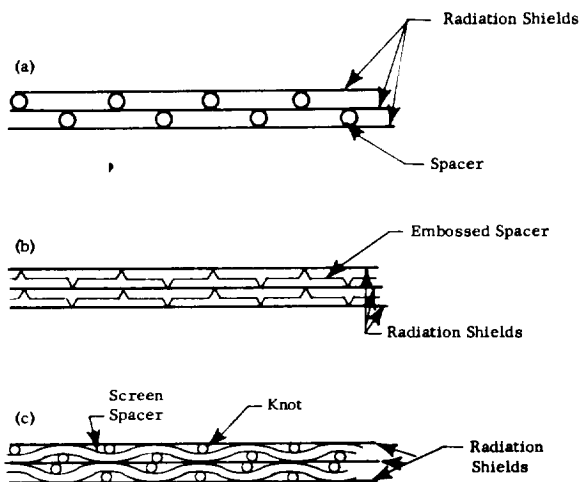
FIGURE 23.—Examples of point-contact spacers: (a) Spheres between shields; (b) point contacts between shields; (c) screen between shields.

Single-component multilayer insulations

Radiation shields can be spaced from each other without using any spacer material. Embossing or crinkling the shields produces random small area contacts that create contact resistances high enough to reduce conductive heat transfer to a value comparable to the amount of heat transferred by radiation through the same assembly of radiation shields.

This method of spacing can only be used with radiation shields of low conductivity such as thin sheets of polyester film (0.00025-inch (6.3-micron) thickness) with a metal coating on only one side (ref. 33).

Composite spacers

A detailed investigation (ref. 34) of the thermal behavior of multilayer insulation under compressive loads typically applied to an insulation during installation led to a concept of a spacer consisting of two or more materials. Each material is selected to perform a specific function. A composite spacer may consist of a very light, dimensionally stable, thin material of tensile properties that will permit easy application of the insulation. The thermal properties of this material are not of primary importance, because it is used only as a "carrier" to which a material of desired thermal properties is attached. The second material is not required to have any specific tensile strength or dimensional stability but only acceptable thermal properties. This concept permits a designer to select materials best suited to specific functions and the desired performance for the complete assembly.

Spacer materials

Table 2 lists typical materials that can be used as spacers for multilayer insulations. Depending on the required performance, one or more layers of the spacer material may be applied between each two neighboring radiation shields.

The selection of a spacer material is guided by the following criteria:

- Insulation effectiveness in operating environment
- System weight
- Thickness limitation
- Method of attachment
- Number, size, and shape of penetrations
- Assembly procedures
- Preoperational storage and shipping conditions
- Cost effectiveness

TABLE 2.—*Comparison of Typical Spacer Materials*

Spacer material	Thickness, in.	Weight per area		Dimensional stability	Tensile strength
		lb/ft² (×10⁻³)	g/m²		
Foam_____	0.020	3.3	16	Good	Poor
Glass paper_____ {	.08	10.9	53	Fair	Poor
	.04	6.1	30	Fair	Poor
Crinkled polyester film_____	.00025	1.5	7.3	Poor	Excellent
Glass fabric_____	.0015	3.8	19	Very poor	Poor
Silk screen_____	.003	1.2	5.9	Good	Good
Nylon screen_____	.007	2.7	13	Good	Good
Vinyl-coated fiber-glass screen__	.020	15.4	75	Excellent	Excellent

To reduce the weight of the spacer, the material may be perforated, as long as the perforation is consistent with the conduction heat transfer limitations. Reducing the load-carrying areas of the spacer materials requires that the remaining areas carry increased compressive loads. A balance between the desire to reduce weight and the capability of the spacer material to carry loads without suffering a substantial increase in heat transfer has to be established for each spacer material. Multilayer insulations with composite spacers designed to carry loads and to withstand the operational environment are shown in figures 24, 25, and 26.

Radiation Shields

The primary requirement for a radiation shield is that it exhibit a low emittance. Silver, aluminum, and gold are low-emittance materials that can be used either as coatings for radiation shields or to form thin foils. A comparison of the emittance of metal-coated films is shown in figure 27. Aluminum and aluminum-coated plastic films are most frequently selected for the radiation shields because: (1) the emissivity of aluminum is only slightly higher than that of clean silver; but, whereas silver tarnishes in air, aluminum forms a very thin layer of aluminum oxide which prevents further degradation of the surface; and (2) aluminum is inexpensive and readily available in various thicknesses of foil and as a coating on a variety of metallic and nonmetallic surfaces.
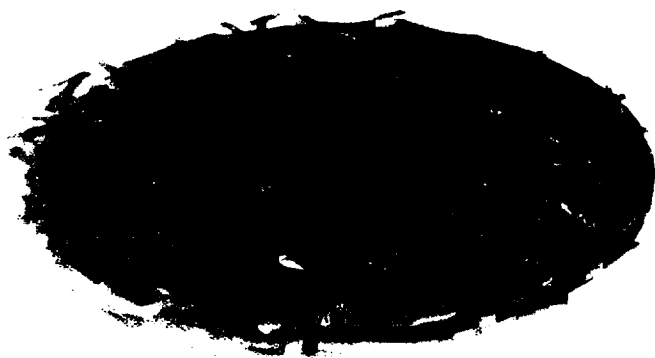
FIGURE 24.—Foam strips cemented on silk-screen carrier.
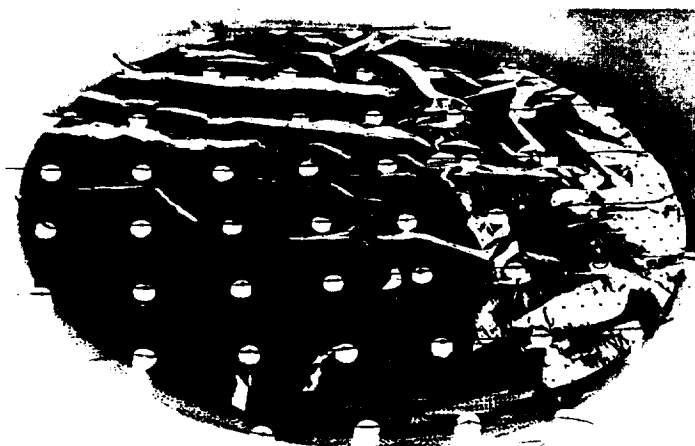
FIGURE 25.—Multilayer insulation with composite material spacer (glass-paper disks on silk-screen carrier).

FIGURE 26.—Multilayer insulation with composite foam spacer.
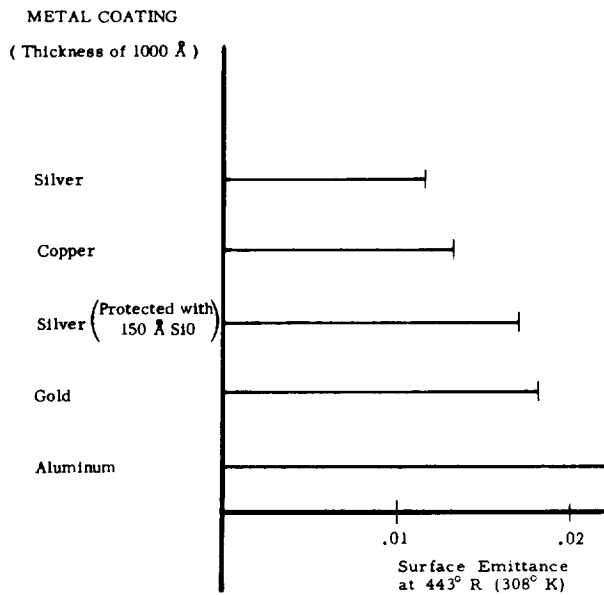
FIGURE 27.—Emittance of metal-coated films.

In applications where weight is at a premium, 0.00025- and 0.0005-inch-thick (6 to 12 microns) aluminum foils are used for radiation shields even though these foils have very little tensile strength and are difficult to handle. Heavier foils (0.001 to 0.005 inch (25 to 125 microns)) find only a limited application where the weight is of secondary importance to: (1) ease of handling, (2) tendency not to bridge between the support points, and (3) maintenance of a given structural shape.

Use of 0.00025- to 0.0005-inch-thick metal-coated plastic films results in a further reduction in weight (plastic films are approximately one-half the weight of aluminum foils of equivalent thickness). In addition to the weight saving, 0.00025-inch-thick polyester film offers a tear strength far superior to that of even 0.0005-inch-thick aluminum foil. Most polyester films, however, are limited to operating temperatures below 300° F (150° C), the point at which the film begins to deteriorate (although polyimide film can withstand temperatures as high as 750° F (400° C)). Aluminum foils can be used in temperatures up to 1000° F (540° C) (ref. 7).

The plastic film can be coated with metal on one or both sides, depending on the application. Single-component multilayer insulations (ch. 4, p. 42) are normally coated on one side to prevent metal-to-metal contact between two neighboring radiation

shields. The emittance of an uncoated side is higher than that of a coated side (approximately 0.35 for 0.00025-inch-thick film). More radiation shields are required to reduce the radiation heat transfer to the level that can be achieved by coating both sides.

Tests have shown that metal coatings less than 500 Å thick are transparent to the radiation, while reflective properties of coatings more than 1000 Å thick change very little with the coating thickness. (See fig. 28.) Because of the present state of the art, metal is coated over the plastic film by deposition of a vaporized pure metal in a vacuum. The process produces a clean, uniform, highly reflective metal layer over the film.

Aluminum vaporizes at a lower temperature than gold, making the aluminum deposition process easier to control. Plastic films with an aluminum deposit have been used for decorative purposes in industry for many years. As a result, aluminum-coated films are less expensive and of a better average quality than gold- or silver-coated films. (The amount of metal used in the deposition process is small so that the cost of gold causes only a negligible increase in the price of the gold-coated film over that of aluminum-coated film.)

Checks of the thickness of metal deposits can be made by one of the methods described in references 7 and 9. Two simple checks used for quality control are the measurement of electrical resistance and the weight of the deposited metal. (The weight of the deposited metal is determined by weighing the metal-coated plastic film before and after removal of the metal coating by a solvent.)
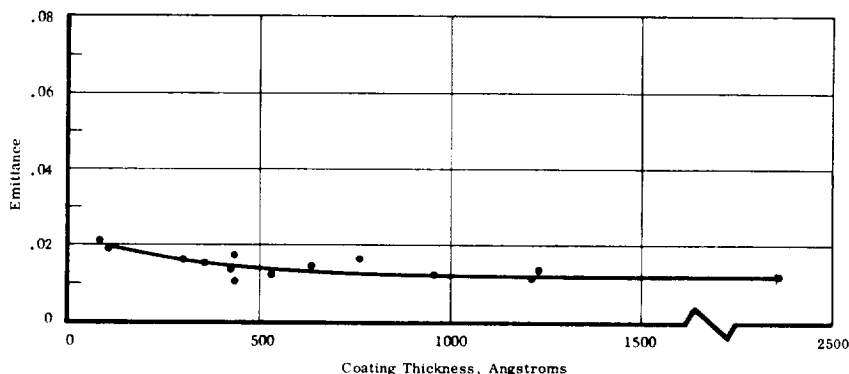
FIGURE 28.—Emittance of polyester film coated with silver. (Silver coating was produced in 18-in. vacuum jar.)

Typical Performance of Multilayer Insulation

Table 3 shows various combinations of spacers and radiation shields that have been tested and reported in references 4, 7, 9, 15, and 34–38.

The table summarizes the performance of several multilayer insulations at zero compressive loads and at loads of 15 psi. The insulations were tested between room temperature and the temperature of a boiling cryogen (liquid nitrogen or liquid hydrogen). To obtain the best possible performance, the tests were performed under carefully controlled conditions.

The performance of any given insulation in an actual installation will be greatly affected by the following variables:

- Applied compressive load
- Number of shields used in the sample
- Kind of gas filling the insulation and its pressure
- Size and number of perforations in the insulation to permit outgassing
- Temperatures of the warm and cold boundaries

Effects of compressive loads

Compressive loads, either those caused by atmospheric pressure, when a flexible outer skin is used to contain the insulation and permit evacuation, or those developed during application of multilayer insulations, reduce overall insulating effectiveness. Even if the compression by the weight of the upper layers on the lower layers is disregarded, external forces (e.g., tension applied during wrapping of a multilayer insulation around a cylindrical object, thermal expansion or contraction of the insulation components with respect to the object, and localized loads in the vicinity of the object's supports) can compress the insulation.

These compressive loads may be in the range from 0.01 to 1 psi (0.0048 to 0.48 g/cm^2). Figure 29 shows the effects of compression on the heat flux through 16 different multilayer insulations. When compression up to 2 psi (0.96 g/cm^2) is applied, the heat flux for the majority of the insulations is about 200 times greater than at the no-load condition. As shown in figure 30, plots of the heat flux (characteristic also of the apparent thermal conductivity) versus compressive load on a logarithmic scale fall on straight lines with a slope between 0.5 and 0.67.

Effects of number of radiation shields

In theory, the heat flux passing through an uncompressed sample of the multilayer insulation is inversely proportional to the

TABLE 3.—*Thermal Conductivity of Typical Multilayer Insulation*

Material	Thickness, in.	Properties at optimum density					Properties at 15-psi (1 kg/cm²) compression			
		Apparent thermal conductivity		Density		Number of shields/in.	Apparent thermal conductivity		Density	
		Btu-in. hr-ft²°F. (×10⁻⁴)	µW cm-°C.	lb/ft³	mg/cm³		Btu-in. hr-ft²°F. (×10⁻⁴)	µW cm-°C.	lb/ft³	mg/cm³
Systems with 0.00025-in.-thick aluminum-coated polyester radiation shields										
No spacer, crinkled shield aluminized on 1 side only		2.0	0.29	1.4	22	67	410	59	29	470
Polyurethane foam 2 lb/ft³ (32 mg/cm³) density	0.020	1.0	.14	1.4	22	151	68	10	3.0	48
Polyurethane foam 2 lb/ft³ density 11 percent support area	.020	.8	.12	.83	13	20				
Polyurethane foam 2 lb/ft³ with polyurethane foam grid ¼ in. wide on 1½-in.-centers	.020	2.4	.35	1.3	21	9	70	10	48	770
2 layers fiber-glass cloth	.001	1.3	.19	5.2	83	47	830	120	30	480
1 layer fiber-glass cloth	.001	1.0	.14	13.6	218	210				
⅛-in. by ⅛-in. mesh vinyl-coated fiber-glass screen	.020	4.3	.62	6.4	103	30	180	26	9	140
Nylon screen	.007	.56	.084	3.0	48	50				

2 1/16-in. by 1/16-in. mesh silk screens (ea)	.003	3.0	.43	1.4	22	30	42	6.1	12	190
3 1/16-in. by 1/16-in. mesh silk screens (ea)	.003	2.5	.36	1.4	22	22	18	2.6	16	260
One 1/16-in. by 1/16-in. mesh silk screen with—										
Fiber-glass paper	.008	3.0	.43	6.0	96	19	58	8.4	15	240
1/4-in.-wide fiber-glass strips	.008	2.0	.29	1.9	31	22	41	5.9	11	180
1/2-in.-wide fiber-glass strips	.004	4.2	.60	1.7	27	20	41	5.9	13	210
1/4-in.-wide flexible foam strips	.100	5.5	.79	.74	12	9	180	26	9	140
1/4-in.-wide rigid foam	.100	3.6	.52	.62	10	10	130	19	4.4	71
Fiber-glass paper 50 percent perforated	.008	2.0	.29	3.7	59	32	87	13	20	320

Systems with 0.0005-in.-thick soft aluminum radiation shields

3 layers fiber-glass cloth	.001	.9	.12	10	160	52	335	48	37	590
Fiber-glass mat	.014	1.0	.14	5	80	22	44	6.4	13	210
Fiber-glass paper	.003	1.2	.17	3	48	36	76	11	24	380

Systems with 0.002-in.-thick H19 tempered radiation shields

Nylon screen	.007	.43	.062	15	240	40	160	23	35	560
1/8-in. by 1/8-in. mesh vinyl-coated fiber-glass screen	.020	1.6	.23	16	260	30	---	---	---	---
Impregnated fiber-glass mat	.020	1.2	.17	12	190	22	80	12	32	510
Impregnated fiber-glass mat with 89 percent perforation	.020	.7	.10	10	160	23	---	---	---	---
Do	.080	3.3	.48			7				
Fiber-glass paper 50 percent perforated	.008	1.6	.23	13	210	33	150	22	50	800

TABLE 3.—*Concluded*

Material	Thickness, in.	Properties at optimum density					Properties at 15-psi (1 kg/cm²) compression			
		Apparent thermal conductivity		Density		Number of shields/in.	Apparent thermal conductivity		Density	
		Btu-in. / hr-ft²-°F. (×10⁻⁴)	μW / cm-°C.	lb/ft³	mg/cm³		Btu-in. / hr-ft²-°F. (×10⁻⁴)	μW / cm-°C.	lb/ft³	mg/cm³
Systems with other radiation shields										
Silver-coated polyester film silk screen with ¼-in.-wide flexible foam strips.	.0005 .003 .100	5.4	.78			8				
Gold-coated polyester film with 2 layers of silk screen per spacer.	.00025 .003	3.1	.49	1.0	16	24				

ᵃ Radiation shields 0.0001 in. thick.

Sample No.	T_{cold}, °F	Number of layers	Description
1031	-320	20	Aluminized polyester film
		11	Fiber-glass mesh
1032	-423	10	Tempered aluminum
		11	Perforated fiber-glass mat
1033	-423	11	Aluminized polyester film
		10	Perforated fiber-glass mat
1058	-423	11	Tempered aluminum
		10	CT-449 (0.020 in.)
1064	-423	11	Aluminized polyester film
		11	Polyurethane foam
1065	-423	10	Aluminized polyester film
		11	Polyurethane foam (11 percent support)
2005	-320	60	Aluminized polyester film
		61	Fiber-glass cloth
2006	-423	20	Soft aluminum
		21	Polyester film
2013	-423	10	Tempered aluminum
		10	0.003-inch glass-fiber paper
2028	-423	10	Waffled aluminum
		11	Fiber-glass mat
2029	-428	10	Waffled aluminum
		11	Three-layer fiber-glass cloth
2038	-423	10	Tempered aluminum
		11	CT-449 (11 percent support area, 0.020 in.)
2039	-423	10	Double aluminized polyester film (both sides)
		11	Nylon netting (0.007 in.)
2040	-423	10	Tempered aluminum
		11	Nylon net
3001	-320	60	Crinkled, aluminized polyester film
3027	-320	6	Aluminized polyester film
		7	CT-449 (11 percent support area, 0.080 in.)

FIGURE 29.—Effect of mechanical loading on the heat flux through multilayer insulations.
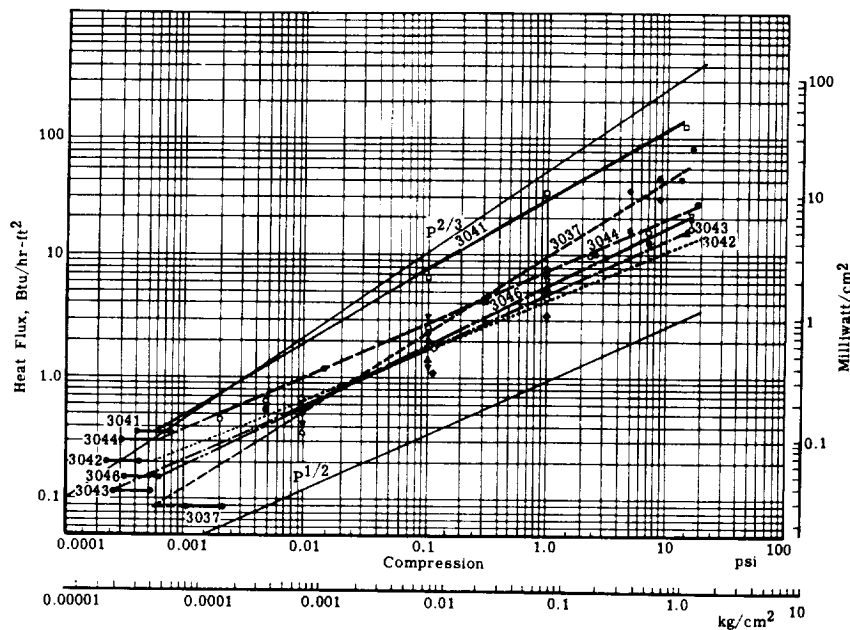
	Run No.	Number of layers	Material
- - -O- - -	3037	10	1145—H19 Tempered aluminum
		11	Nylon netting
—□—	3041	10	Aluminized (both sides) polyester
		22	Glass fabric
- - -◇- - -	3042	10	Aluminized (both sides) polyester
		33	Silk netting
—·△·—	3043	10	Aluminized (both sides) polyester
		11	2 lb/ft³ polyurethane foam
—O—	3044	10	Aluminized (both sides) polyester
		11	Silk netting with 0.004-in. by 0.5-in. strips of glass mat
—··▽··—	3046	10	Aluminized (both sides) polyester
		11	Silk netting with 0.008-in. by 0.25-in. strips of glass mat

● Increasing compression.
O Decreasing compression.

FIGURE 30.—Effect of external compression on the heat flux through multi-layer insulations.

sample thickness (i.e., number of shields), and, therefore, its thermal conductivity can be evaluated. Figure 31 shows that in the first approximation the heat flux is indeed inversely proportional to the number of shields. However, the experimentally obtained heat-flux data for a sample with 40 shields are somewhat higher than predicted from the 5-shield sample data. In figure 31, the solid line which passes through 2 experimental points for 5- and 10-shield samples predicts heat fluxes for 20- and 40-shield samples lower than were actually observed. This discrepancy may be explained by the compression exerted by
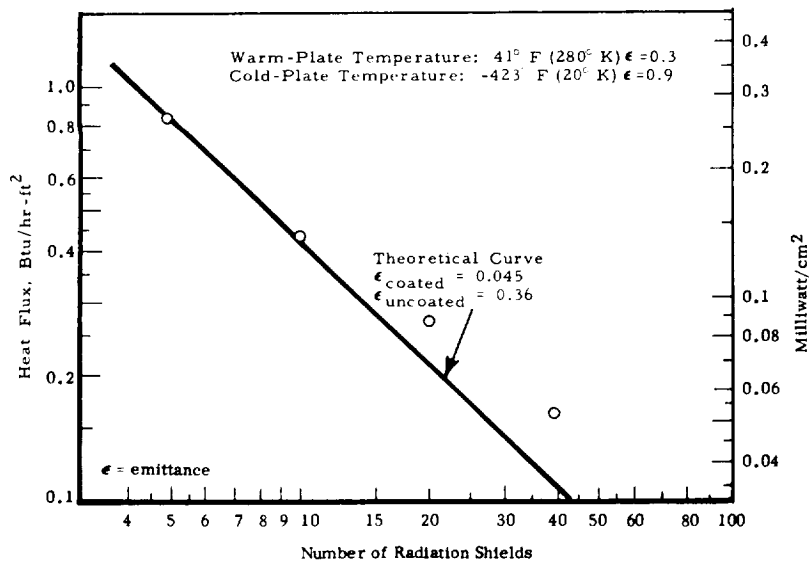
FIGURE 31.—Effect of number of radiation shields on net heat flux.
(Radiation shields: crinkled aluminum polyester film. Spacers:
⅛- by ⅛-in. mesh vinyl-coated fiber-glass screen.)

the weight of the upper layers on the lower layers of the sample,
which may cause the lower layers to perform less efficiently than
the upper layers. If an accurate estimate of the heat flux is re-
quired, a correction factor for the effect of compression (ch. 4,
p. 42) must be applied.

Effects of type of gas and gas pressure

The effects of a gas and its pressure on the performance of
insulations have been studied by many investigators (refs. 9, 15,
36, 39–41). The presence of residual gas inside fibrous and pow-
der insulations decreases the thermal performance of a system.
Gases of high thermal conductivity (e.g., helium or hydrogen)
cause more rapid performance deterioration than gases with low
conductivity (e.g., nitrogen or air). These effects are even
more pronounced for a multilayer insulation. The effect of gas
pressure on the thermal conductivity of several multilayer insu-
lations is shown in figure 32. For comparison purposes, data for
one fibrous insulation (glass wool in air) are plotted in the same
figure.

The thermal conductivity relates to gas pressure by an S-
shaped curve. However, the effect of pressure on performance of
multilayer insulations is 2 magnitudes larger than the effect of
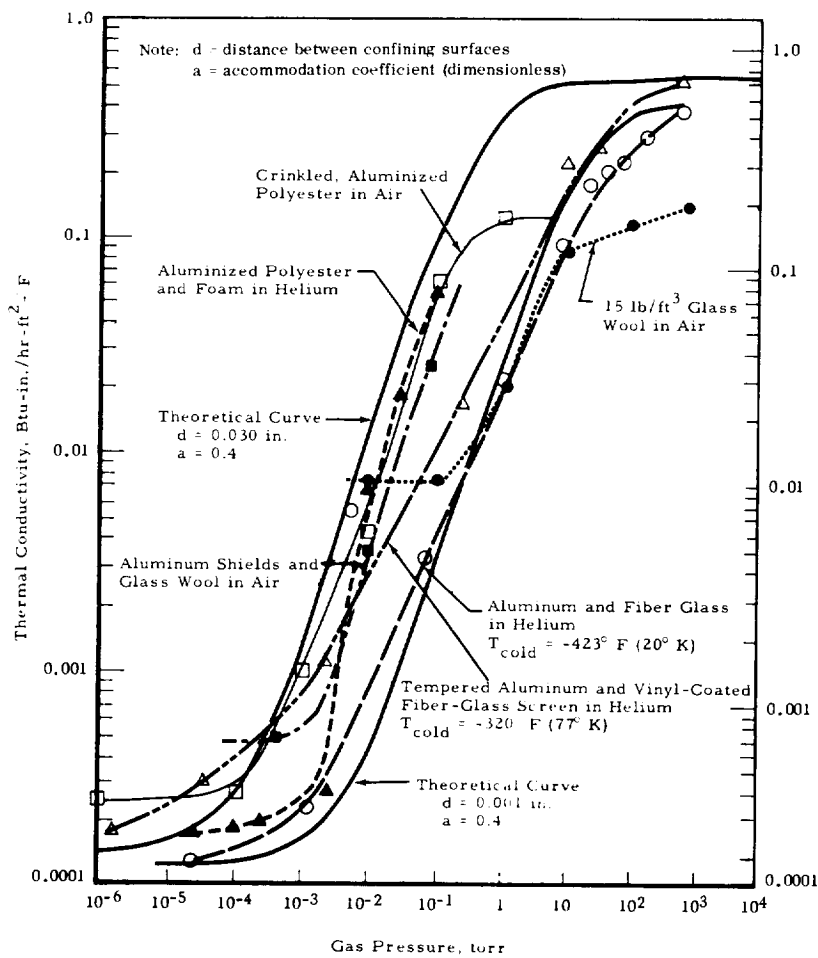
FIGURE 32.—Effect of gas pressure on thermal conductivity.

pressure on powder or fibers (i.e., the performance of a multi-layer insulation is 100 times higher than that of a powder, but a pressure 100 times lower is required to reach it). At pressures below 10^{-5} torr, the heat transferred by a gas is directly proportional to the gas pressure. However, the heat conducted by a gas at that pressure is only a small portion of the total heat transferred through the insulation; therefore, the apparent thermal conductivity of the multilayer insulation decreases only slowly at pressures below 10^{-5} torr.

At pressures of 10^{-5} to 10^{-4} torr, the mean free path of the gas molecules approaches the distance between the solid particles

of the insulation. Beginning at these pressures, the apparent thermal conductivity of the insulation rapidly increases. For this reason the multilayer insulation must be maintained at a pressure below 10^{-4} torr or it will not provide the desired insulation effectiveness.

When the gas pressure reaches atmospheric pressure, the heat conducted by the gas becomes the dominant mode of heat transfer. For a warm boundary at room temperature, the radiation component becomes small in comparison to the gas conduction component. Therefore, the apparent thermal conductivity of a multilayer insulation approaches the conductivity of the interstitial gas. After atmospheric pressure has been reached, the conductivity of the gas remains nearly constant and independent of the pressure, as does the apparent thermal conductivity of a multilayer insulation.

Effects of perforations

To assure that multilayer insulations will operate at the desired low pressure, the interstitial gas has to be evacuated through the edges of the insulation. For an insulation with 100 shields per inch and spacers that effectively occupy 90 percent of the spaces between the shields, the maximum outgassing rate corresponds to the removal of one monomolecular layer from all exposed insulation surfaces every 2 weeks (ref. 41). Because much higher outgassing rates are likely to be encountered after the radiation shields and spacers have been exposed to atmospheric gases during manufacture, edge pumping by itself will not be adequate to insure a low pressure within the insulation within a reasonable time.

Another difficulty with edge pumping is that, at the exposed edges, the innermost radiation shields have to be brought into contact with a warmer outside boundary. This contact may permit radiation to bypass most of the shields and penetrate almost directly to the insulated object.

Broadside pumping of a multilayer insulation is made possible by perforating the radiation shields. If the perforations comprise 10 percent of the area of the shields, broadside pumping will increase the outgassing rate by 3 orders of magnitude as compared to edge pumping and will produce a satisfactory low pressure in a short time. However, perforation of the radiation shields will lead to an increase in their effective emittance; if an unperforated shield has an emittance of 0.05, perforating 10 percent of the shield area will increase the emittance to 0.25.
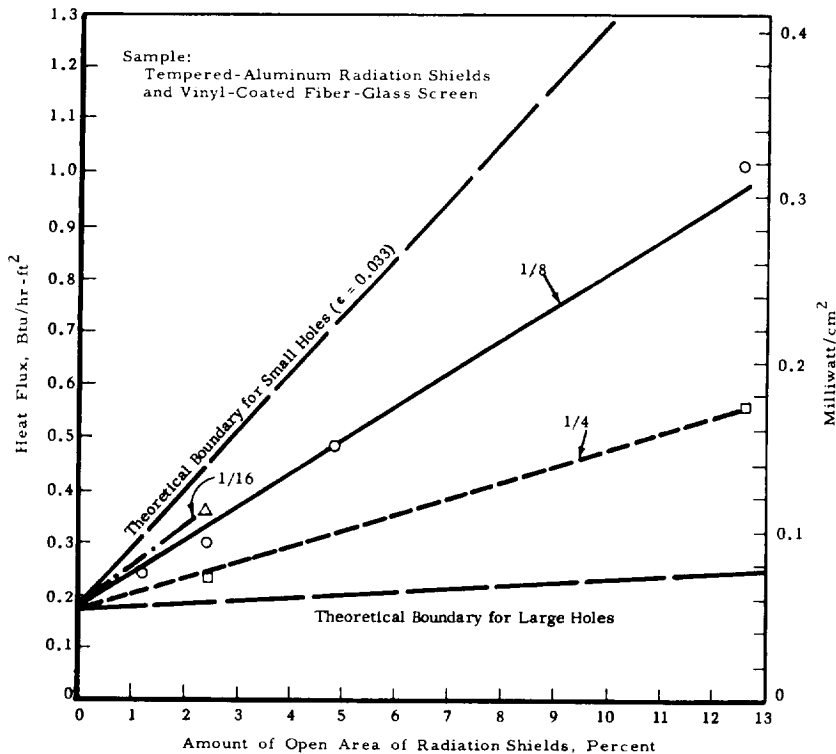
FIGURE 33.—Effect of perforations on heat flux. (Hole diameter: 1/16 in., 1/8 in., and 1/4 in.)

Thus, a compromise must be reached between a sufficiently high pumping speed and a reduction in insulating effectiveness.

For the same amount of open area, optimum pumping and outgassing efficiency is obtained with many small holes rather than a few large holes (ref. 41). However, small holes cause a higher heat flux, as is observed from figure 33 which shows two theoretical limits, one for extremely small holes, the other for large holes. Experimental data for holes 1/16, 1/8, and 1/4 inch in diameter fall as expected within these limits.

Figure 34 shows that perforations have a smaller effect on an insulation with crinkled, aluminized polyester shields than on one with aluminum shields, presumably because the crinkles introduce a more random distribution of the holes.

Effects of the boundary temperature

Table 4 and figure 35 illustrate the effect of the warm- and cold-boundary temperatures on the heat flux through multilayer in-
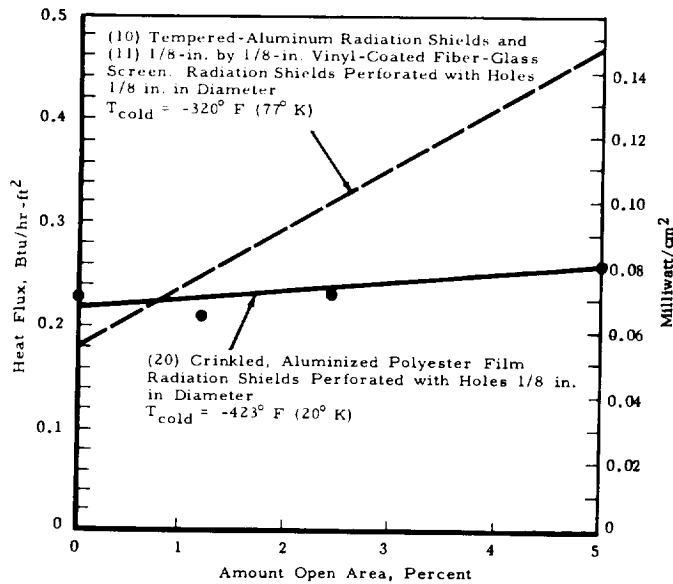
FIGURE 34.—Effect of perforations on the heat flux through
a multilayer insulation.

sulations. Table 4 gives the heat flux through various insula-
tions for which the cold-boundary temperature was changed from
$-320°$ to $-°423°$ F ($77°$ to $20°$ K). The heat flux through each
sample is approximately the same for both temperature levels.

Figure 35 shows heat-flux versus warm-boundary temperature
for 10 tempered aluminum shields spaced with 11 vinyl-coated
fiber-glass-screen spacers. For large temperature differentials, heat
flux is directly proportional to the fourth power of the warm-
boundary temperature.

The two curves of figure 36 show the apparent thermal con-
ductivity versus warm-boundary temperature calculated from the
heat flux data. The one that represents a cold-boundary temper-
ature of $-423°$ F ($20°$ K) indicates a lower thermal conductivity
than the one representing a cold-boundary temperature of
$-320°$ F ($77°$ K). Thus, when the warm-boundary temperature
is held constant, a higher thermal conductivity results from in-
creasing the cold-boundary temperature.

Apparent thermal conductivity is approximately proportional
to the third power of the warm-boundary temperature, as shown
in figure 37, where the third power of the warm-boundary tem-
perature is matched with experimental results for a multilayer
insulation with crinkled, aluminized polyester film radiation
shields.

TABLE 4.—*The Effect of the Cold-Boundary Temperature on the Heat Flux Through Multilayer Insulations*

Number of layers	Sample	Thickness, in.	Boundary, cold °K	Boundary, cold °F	Temperature, warm °K	Temperature, warm °F	Density g/cm³	Density lb/ft³	Heat flux µW cm²	Heat flux Btu hr-ft²
10	Tempered aluminum foil	0.300	77	−320	290	61	0.21	13	73	0.23
11	50 percent open fiber-glass mat	0.300	20 / 77	−423 / −320	290	61	0.21	13	63 / 285	.20 / .90
20	Aluminized polyester film, crinkled	.385	20	−423	279	42	.02	1.2	276	.87
95	Aluminized polyester film	.385	20 / 77	−423 / −320	286	55	.31	20	133	.42
96	Glass fabric	.800	20	−423	286	55	.31	20	136	.43

FIGURE 35.—Effect of warm-boundary temperature on heat flux through a multilayer insulation.
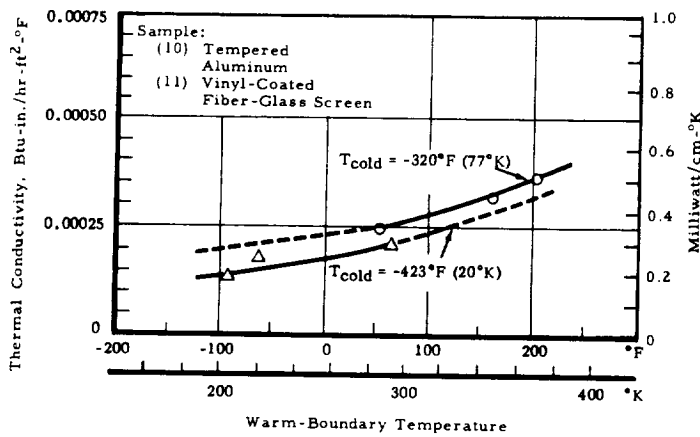
FIGURE 36.—Effect of boundary temperature on the mean apparent thermal conductivity of a multilayer insulation.

Foams

Types of Foams

Organic and inorganic foams are commonly used as insulating materials in industrial and construction applications. Because
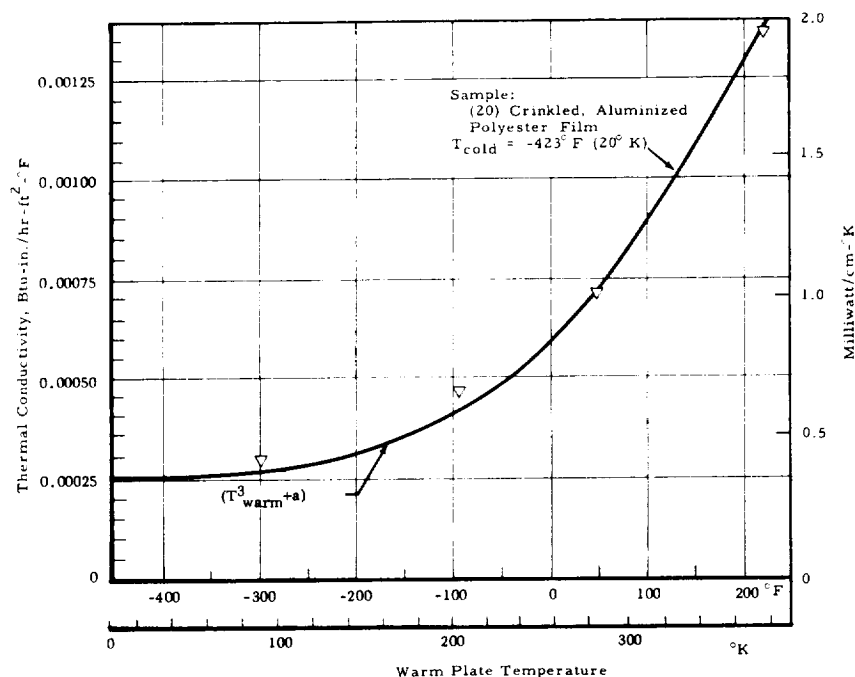
FIGURE 37.—Effect of boundary temperature on thermal conductivity of
crinkled, aluminized polyester film.

such foams have many advantages for cryogenic and space-
vehicle applications, efforts have been made to develop suitable
foam formulations; establish the physical, chemical, and struc-
tural properties of foams; and integrate foams with thermal in-
sulation systems. Having a cellular structure of discrete or inter-
connected voids, the foams provide effective insulation. Inorganic
foams are used primarily at elevated temperatures. (See ch. 4.)

Inorganic foams are difficult to produce in densities of 1 to 5
lb/ft³ (0.016 to 0.08 g/cm³) and generally have inferior phys-
ical properties at these low densities. Organic foams can be
readily made in this low-density range and exhibit good physical
properties. For many insulation applications, low-density organic
foams offer certain advantages, which include:

● Ease of fabrication
● Relatively low cost
● Self-supporting structure

Foams can be used either as a single insulation or combined with
other materials to form a thermal insulation system. Like plas-
tics, organic polymer foams can be divided into two basic clas-
sifications.

Thermoplastic foams

Thermoplastic foams soften at temperatures of 150° to 250° F (65° to 120° C), and, in most cases, tend to become brittle at cryogenic temperatures. Thermoplastic foams can be made from such polymers as cellulose acetate, polystyrene, styrene-acrylonitrile copolymer, polyvinyl chloride, polyethylene, and polypropylene. Of these foams, polystyrene and polyvinyl chloride are by far the most common.

Polystyrene foams can be subdivided into two basic types: molded expandable beads and extruded foam. Limited use has been made of polystyrene foams in cryogenic insulation applications; their utility is limited by low-temperature embrittlement and inability to withstand extreme thermal cycling. Until recently, most polyvinyl chloride foams were flexible formulations, which also suffer from severe low-temperature embrittlement. Recently, rigid polyvinyl chloride foams of high density have become commercially available, and they are used for insulation and structural support of tanks for transporting liquefied petroleum gas.

Thermosetting foams

Among the thermosetting polymers, foams are commonly made with phenolic, urea-formaldehyde, epoxy, and polyurethane resins. Urea-formaldehyde foams are brittle and do not have good structural properties at low densities. At low densities the phenolic resin foams tend to be brittle and friable at room temperature and are difficult to fabricate because the formation of the foam requires the use of a strong acid catalyst and highly volatile, flammable blowing agents. Epoxy foams have had only limited use because of the difficulties in satisfactorily controlling the foaming. They also exhibit only fair physical properties and are relatively expensive.

Among the thermosetting foams, polyurethanes are by far the most widely used in industrial and building applications and in cryogenic insulation. Urethane foams are made by the reaction of two liquid chemical compounds containing two or more isocyanate groups with another compound, called a polyol, which contains two or more hydroxyl groups. The formulation contains small amounts of other additives to expand the mixture, catalyze the reaction, and control cell structure. The foam may be either a one-shot type, in which the polyol-plus additives are added directly to the isocyanate to produce the foam, or it may be a prepolymer type, in which the isocyanate is first reacted with a portion of the polyol and then more polyol and other additives

are added to the prepolymer to make the foam and complete the curing reaction.

Polyurethane foams can use either of two types of foaming techniques:

● The isocyanate groups will react with water to produce carbon dioxide. If water is included in the polyol side of the formulation and the proper adjustment of quantity of isocyanate is made, the carbon dioxide generated by the reaction of water with isocyanate when the two components are mixed will produce a foam from a liquid mix. Following foaming, the polyol and isocyanate will continue to react to cure the foam. These types of foams exhibit better high-temperature physical properties than foams blown with other gases.

● The foaming technique that is more commonly used is fluorocarbon blowing; a fluorocarbon liquid, which will boil slightly above ambient temperature (usually about 75° F (24° C)), is added to the polyol side of the foam formulation. When the components are mixed, the curing reaction liberates heat which raises the temperature of the liquid mix above the boiling point of the fluorocarbon which then vaporizes to foam mixture. Most polyurethane foams of either the carbon dioxide-blown or fluorocarbon-blown type cure relatively quickly. The foaming occurs within 1 to 3 minutes after the components are mixed, and curing proceeds to a tack-free surface within 5 to 15 minutes. The fluorocarbon-blown foams have become much more common than the carbon dioxide-blown foams because the fluorocarbon system provides better control of the foaming reaction and foam structure and lower thermal conductivity in the foam. This lower conductivity results directly from the lower conductivity of fluorocarbon in the foam cells in comparison with carbon dioxide.

Depending on the chemical composition of the starting isocyanate and polyol, the physical properties of polyurethanes can vary from very soft and flexible cushioning materials to hard, rigid foams. Two basic types of polyols are used: polyesters and polyethers. Depending on the type of polyol, the resulting product may be called either a polyester foam or a polyether foam.

Polyurethanes, in general, and some of the semirigid formulations, in particular, have very good properties at cryogenic temperatures with a minimum tendency to become brittle.

Intermediate foam

One other type of polymer foam is tetrafluoroethylene (TFE), an intermediate between a thermosetting and a thermoplastic

foam, which melts at very high temperatures and has very good physical properties at cryogenic temperatures. In addition, TFE's extreme chemical inertness makes it resistant to the effects of liquid oxygen, hydrazine, and other chemically reactive rocket fuels. Tetrafluoroethylene foam has found limited use; that is, as thermal insulation and a resilient mounting pad in space applications.

Application of Foam

Techniques to reduce the effects of thermal expansion and contraction

In the selection of foams and the design of an insulation system, one has to take into account the variation in the thermal expansion coefficient of various polyurethane foams, depending on the particular formulation; but, in general, the thermal expansion coefficient of such foams is 2 to 5 times that of aluminum and 4 to 10 times that of steel. The foam insulation must be designed to accommodate this difference in thermal expansion coefficients between the foam and the surface of the metal cryogenic tanks. The foam cannot be foamed in place against the metal or bonded directly to it because, during chilldown from ambient temperature to cryogenic temperatures, the contraction of the foam adjacent to the surface of a metal tank will be substantially higher than the contraction of the metal. As a result, high stresses will be created in the foam and it will fail either in shear along the tank surface or in tension in a direction normal to the tank surface. This problem was recognized early in the development of cryogenic insulation systems (ref. 42).

A sprayed foam insulation was applied to a cryogenic tank, but on the first cooldown the insulation developed radial and longitudinal cracks which tended to propagate during subsequent thermal shocks. Large cracks were patched with a flexible foam and covered with a tape as a vapor barrier. The foam sheared from the tank surface, so that metal bands had to be used to secure it in place.

Various techniques for overcoming the effects of thermal contraction on chilldown have been developed. In connection with an investigation of multilayer insulation systems, a number of different prepolymer foams were foamed in place against a metal plate (ref. 30). The foam thickness was about ½ inch. After the foam had cured, the plate was first chilled with liquid nitrogen and then the entire assembly was immersed in liquid nitrogen. Although there were differences in the amount of cracking that occurred, all of the foams failed in this test: the foam either

sheared from the metal plate or tensile failure produced cracks through the foam normal to the metal plate.

To overcome this difficulty, chopped glass fibers, ¼ to ½ inch long, were added to a low-viscosity one-shot foam mix to reinforce the foam. Additions of 5 percent fiber by weight (based on the weight of foam) reduced the amount of cracking on exposure to liquid nitrogen, but some cracking still occurred. With a 7-½-percent fiber addition, very slight cracking occurred, and at a 10-percent addition no cracking occurred. In further tests of the durability of the 10-percent reinforced foam, a strip 1 inch wide by 10 inches long with ½ inch of foam on it was immersed in liquid helium with no failure. Similarly, several samples were prepared and immersed in liquid hydrogen with no failures.

In work on the Saturn S–IV stage, where an internal insulation system was developed for the liquid-hydrogen propellant tank, a technique for reinforcing the urethane foam with threads (called 3D foam) was used to prevent foam failure and separation of foam panels or fragments from the tank wall and resultant heat leaks and possible clogging of fuel lines (ref. 43).

Techniques to reduce fire and explosion hazards

Reinforcing and sealing a foam on the interior of a liquid-hydrogen tank reduces the potential hazard caused by external sources. The more common approach, however, is to apply foam to the exterior of the tank. When external foam insulation is used, atmospheric gases can condense on the cold tank surface. This effect can be used advantageously in foamed insulation to achieve a low thermal conductivity. When gases in the foam condense, a vacuum is created in the closed cells of the foam. However, if there is any diffusion of air into the foam, the amount of condensed air can increase inside each of the cells. The condensed air will be oxygen rich; in conjunction with an oxidizable organic foam, this oxygen-enriched liquid air can create an explosion hazard. The combination of oxygen-enriched liquid air and an oxidizable organic material is a hazard even if the foam is of the flame-retardant type.

The hazards of fire and explosion associated with a foam insulation system have been recognized. Various mixtures of liquid oxygen and liquid nitrogen in combination with organic insulation containing foam were investigated to determine whether there was indeed a fire or explosion hazard in the event of impact or shock (ref. 44). In this investigation, small test tanks, with an insulation similar to that proposed for the Saturn S–II

stage, were filled with liquid hydrogen, stored for various lengths of time, and then subjected to impact. The results of these tests confirmed that catastrophic failures could occur when the liquid oxygen percentage in a liquid oxygen-liquid nitrogen mixture exceeds 30 percent, but the findings suggested that the probability of such a failure was very low.

Additional tests were conducted to evaluate the explosion and fire hazards of insulation in contact with oxygen-rich slurries and liquid and solid air (ref. 45). In these tests one flat aluminum tank was protected with 0.8-inch-thick and another with 1.6-inch-thick composite sealed insulation. The insulation consisted of fiber-glass phenolic honeycomb filled with polyurethane foam of 2 lb/ft^3 (0.032 g/cm^3) density with the surface sealed with a reinforced-plastic surface layer and a vapor barrier of polyvinyl fluoride. The entire assembly was bonded together and bonded to the tank. There was no provision for purging the insulation with helium.

In the tests, each tank was filled with liquid hydrogen and allowed to cryopump for 2 hours. The tanks were then impacted 6 times with 22-caliber cartridges having a muzzle energy of 38.8 lb-ft (53.8 kg-m) from a distance of 20 feet. There was no sign of any explosion or ignition. With these holes in the insulation, the tanks were exposed to the atmosphere for an additional 4 hours while filled with liquid hydrogen and then 6 more shots were fired. Again, there was no sign of ignition or explosion. The insulated tanks were again kept full and exposed to air for an additional 6 hours (12 hours' total exposure). Following the 13th shot at the tank with the 0.8-inch-thick insulation, damage to the insulation made it impossible to refill the tank with liquid hydrogen. The tank was therefore allowed to warm up gradually, and the muzzle energies of the shots were gradually increased from 38.8 to 47.7, 68.3, and 77 lb-ft (53.8 to 66.0, 94.2, and 106 kg-m) and, finally, on the 20th shot to 112 lb-ft (154 kg-m). At this point a reaction was observed. At the point of impact the insulation ignited and burning was sustained for approximately 5 seconds. A total of 24 shots was fired at the tank with the 1.6-inch insulation. During the last 12 shots, the vent temperature was gradually allowed to increase and during the last 6 shots the muzzle energy was increased from 38.8 to 112 lb-ft (53.8 to 154 kg-m). On none of these impacts was there any sign of ignition or explosion. These tests again indicated that catastrophic failure is possible, but that this possibility is extremely remote in a well-designed foam insulation system.

As developments have proceeded, additional techniques for increasing insulation effectiveness and reducing explosion hazards have been employed.

Insulation System for Centaur

In the early Centaur liquid-hydrogen tank insulation system, insulating panels were mechanically clamped to the surface of the tank, and a helium purge space was left between the tank and the insulations (ref. 43). This insulation had to be jettisoned on stage ignition. Mechanical problems connected with this system proved extremely difficult to overcome. An alternative insulation system was developed in which a thin film of foam was applied to the tank and then overwound with filaments of fiber glass to provide the necessary compressive stress to overcome a tendency of the foam to crack and the effects of aerodynamic heating and vibration during boost (ref. 43). Other techniques that have been investigated involve formation of channels in the foam or a matrix holding the foam so that the insulation can be evacuated and/or purged with helium (ref. 46). Although there is a basic disadvantage in using helium because of its high thermal conductivity, it is a positive means of overcoming fire and explosion hazards. In addition, helium facilitates the jettisoning of insulation panels from a space-vehicle cryogenic tank wall by preventing possible freezing of atmospheric constituents between the tank wall and the insulation.

Insulation System for Saturn S–1C

The Saturn S–1C first stage involved formulation of a rigid urethane foam of a density of 3 to 4 lb/ft³ (0.048 to 0.064 g/cm³) to meet specific compression requirements and which could be fabricated in large, single-pour castings 2 ft by 5 ft by 6 ft (ref. 47). A foam that could meet this large pour requirement was developed. It had a creep of 4.65 percent on completion of three 1-hour load cycles at 60 psi (4.1 kg/cm²), ten ½-hour load cycles at 55 psi (3.7 kg/cm²), and extended continuous loading at 15 psi (1 kg/cm²). The large foam blocks were X-rayed to assure satisfactory internal quality and uniformity throughout. Sixteen 2-½-ft by 5-½-ft by 6-½-ft rough blocks were produced. Each block required 420 pounds of raw materials mix; the batch was mixed in several containers of 210 pounds each. The components were mixed for 130 seconds and immediately poured into the mold.

To improve the cell structure in the foamed blocks, the layer of polyethylene film was placed over the liquid foam mix as soon as the foam was placed in the mold. A piece of ¾-inch plywood laid on the polyethylene film was forced up during the foam rise to the top of the 30-inch-deep mold. This technique resulted in greater uniformity of foam structure. The technique was recommended for making foams with more uniform cell structure and resultant improved physical properties.

Techniques and formulations were also developed for repairing damaged foam blocks. The techniques involve cutting away crushed cells in the damaged area and any loose foam pieces and then applying a patching compound together with necessary dams or retainers. To avoid enlargements of cracks due to internal pressure of the expanding and curing foam patch, strict limitations were placed on the patch size and the amount of material to be used with a specific formulation.

Physical Properties

Structural properties

The physical properties of various foams were evaluated at temperatures down to liquid-hydrogen temperature ($-423°$ F; $-253°$ C) (refs. 48, 49). In one series of tests, tensile, shear, and compressive strengths were determined on four foams at $250°$, $77°$, $-320°$, and $-423°$ F ($121°$, $25°$, $-196°$, and $-253°$ C). In figure 38 the tensile strength of the foam is plotted against temperatures. These curves show that at $-423°$ F, a urethane foam (A) and epoxy foam (C) had a 62-psi (4.2-kg/cm²) tensile strength. A rigid polyurethane foam (B) had a 28-psi (1.9-kg/cm²) tensile strength, and a flexible polyether foam (D) had a 14-psi (0.95-kg/cm²) tensile strength. At $70°$ F ($21°$ C) the rigid polyurethane foam (B) had a tensile strength of 74 psi (5 kg/cm²), the urethane foam (A) just under 70 psi (4.7 kg/cm²), the epoxy foam (C) 53 psi (3.6 kg/cm²), and the flexible polyether foam (D) approximately 15 psi (1 kg/cm²). At $250°$ F ($121°$ C) the strength of all of the foams was below 19 psi (1.3 kg/cm²).

The shear strength for the same foams is shown in figure 39 as a function of temperature. The maximum shear strength for all foams was reached between the two temperature extremes investigated; it decreased at both of the extremes. Generally, 50 psi (3.4 kg/cm²) is considered the necessary minimum compressive strength. At room temperature, the epoxy foam (C) and the
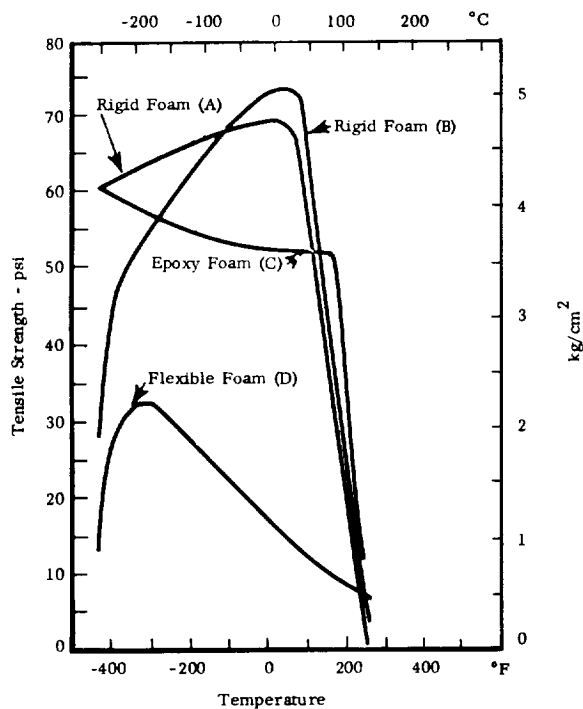
FIGURE 38.—Tensile strength of foams as a function of temperature.

urethane foam (A) took permanent set of at least 20 percent at compressions of 49 and 31 psi (3.3 and 2.1 kg/cm²), respectively. The flexible polyether foam (D) bottomed at 25 psi (1.7 kg/cm²). Although not permanently damaged, under such compression it would no longer be useful as insulation. At room temperature the rigid polyurethane foam (B) withstood 50 psi. The results of the compression tests at −423° F (−253° C) are shown in table 5.

Table 5 shows that the flexible polyether foam (D) retained a degree of resilience even at liquid hydrogen temperature. The polyurethane foam (B) became brittle and yielded, as did the urethane foam (A). The epoxy foam (C) had satisfactory properties at this temperature, although it would not withstand 50 psi at room temperature. These tests generally indicated that none of the tested foams would be fully satisfactory. The flexible foams would be too compressible to retain their thermal characteristics under pressure loadings typically encountered by internal insulation; similarly, if they were to be used as external
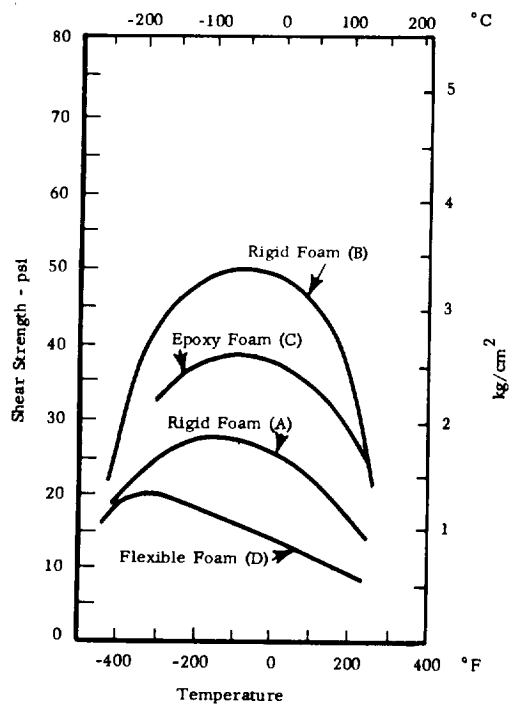
FIGURE 39.—Shear strength of foams as a function of temperature.

insulations, the flexible foams would be too compressible to retain these thermal characteristics under most expected surface loadings. Although most rigid foams lack the necessary strength at either room or cryogenic temperatures, they are used in some applications.

TABLE 5.—*Load-Compression Strength of Foams at* −423°F (−253° C)

Foam	Yield		Set, percent	Compression	
	psi	kg/cm²		Percent at 25 psi (1.7 kg/ cm²)	Percent at 50 psi (3.4 kg/ cm²)
Rigid urethane (A)	28.0	1.9	68.7		30.4
Epoxy (C)			2.8	4.0	6.8
Rigid polyurethane (B)	25.0	1.7	67.4	10.9	82.5
Flexible polyether (D)			7.6	82.6	86.9

Thermal expansion

The thermal expansion properties of various foams are shown in figure 40. This figure shows that although the epoxy foams pose problems, they have the lowest thermal expansion coefficient. It also indicates that all of the foams have reasonably linear thermal expansion characteristics in the cryogenic range. The characteristics become nonlinear only at, and above, room temperature.

Thermal conductivity

Typical thermal conductivity for carbon dioxide-blown urethane foams is about 0.23 Btu-in./hr-ft^2-°F (0.33 mW/cm-°C). For fluorocarbon-blown foams of approximately 2-pound density, thermal conductivity is about 0.12 Btu-in./hr-ft^2-°F (0.17 mW/cm-°C). Fluorocarbon-blown foams will maintain their low thermal conductivity only if the surfaces are sealed to prevent diffusion of the fluorocarbon out of the cells. In thin sections the fluorocarbon will diffuse over a period of time, and the thermal conductivity will gradually rise to about 0.17 Btu-in./hr-ft^2-°F (0.25 mW/cm-°C). For polystyrene foams, the room-temperature thermal conductivity is in the range of 0.23 to 0.26 Btu-in./hr-ft^2-°F (0.33 to 0.38 mW/cm-°C). The thermal con-
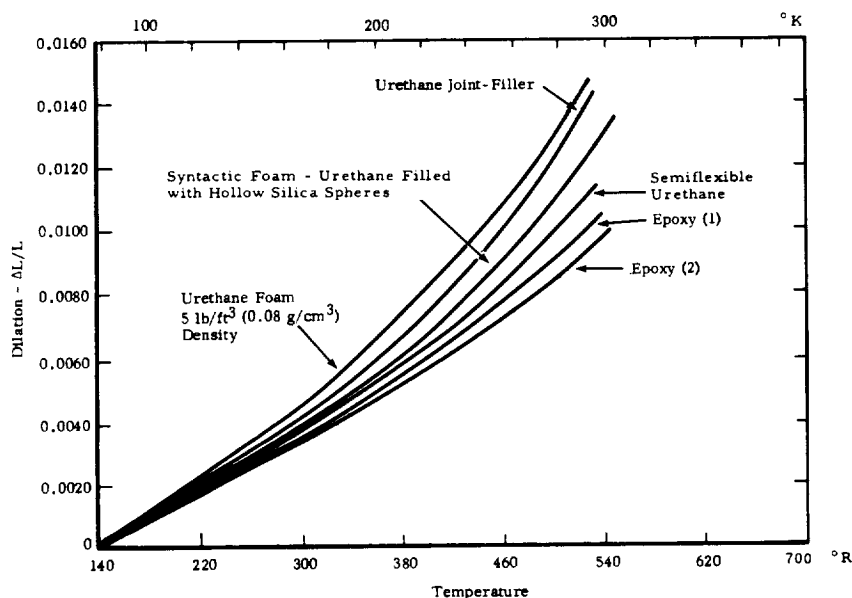
FIGURE 40.—Linear expansion versus temperature for six foam insulations.

ductivity of foams can also be estimated from theoretical considerations (ref. 50).

The thermal conductivity of various foams has been measured over the temperature range of 75° to −423° F (21° to −253° C) (ref. 11). Data were obtained on polystyrene foams, polyurethane foams, composite insulations of foam-filled honeycomb, and tetrafluoroethylene (TFE) sheet materials. These data indicate that for all of the foams tested the thermal conductivity at liquid-hydrogen temperatures is in the range of 0.05 to 0.10 Btu-in./hr-ft²-°F (0.07 to 1.4 mW/cm-°C). As room temperature is approached, these values increase and differences become more pronounced. The differences are attributable to the base resin and in large part to the blowing agent used in making the foam. At liquid hydrogen temperatures, the gases in the cells liquefy or solidify, resulting in a partial vacuum in each cell. At this point, because convection is no longer a mechanism of heat transfer in the foam, the size and uniformity of the cells become the critical factors in determining thermal conductivity. In TFE sheet and TFE-sheet/TFE-foam composite, the reduction in thermal conductivity achieved through the use of the foam is pronounced, even though the conductivity is above that of urethane and styrene foams. Measurements were also made on the thermal conductivity of foams in the presence of helium gas and of air. At a mean temperature of about −385° F (−231° C), the conductivity was in the range of 0.2 to 0.3 Btu-in./hr-ft² -°F (0.29 to 0.43 mW/cm-°C) in comparison with 0.05 Btu-in./hr-ft²-°F (0.072 mW/cm-°C) in air. These data point out the increase in thermal conductivity caused by helium diffusion into evacuated or sealed insulations. In large space-vehicle insulation systems, helium purging is done to reduce potential hazards and to prevent weight increase by atmospheric constituents leaking into the sealed insulation system and condensing or solidifying.

In connection with the use of foams in a space environment, the combined effects of radiation and cryogenic temperatures on insulation materials have been investigated (ref. 51).

Powders and Fibers

Desirable Properties

The desirable properties of an evacuated powder or fiber insulation are:

- Low thermal conductivity
- Low density

- Particle size small enough to obtain the pressure-dependent region of gas conduction in a moderate vacuum
- Distribution of particles by size to minimize effects of shock and vibration
- Low vapor pressure at the operating temperature

The vapor pressure of the material should be as low as is consistent with the desired moderately low operating pressure. Furthermore, transfer of material in the vapor phase from the warmer to the cooler portion of an insulation and subsequent condensation is undesirable because a buildup of deposits between individual particles could increase the areas of contact.

Powder Insulations

Although mica, diatomaceous earth, carbon, calcium silicate, titanium dioxide, iron oxide, and plastic microspheres have been investigated as potential powder insulations; perlite, colloidal silica, and silica aerogel have been investigated more extensively (ref. 52).

Expanded perlite is produced from a volcanic glassy rock that occurs in widely distributed deposits. This rock is ground to a fine powder and then expanded by heating to above 1500° F (800° C). Microscopic voids forming in the expanding, heat-softened glass cause a porous structure and account for the expanded perlite's low density. Perlite is available in various grades containing particles ranging in size from 100 to 1600 microns (4×10^{-3} to 6×10^{-3} in.).

Colloidal silica is a white, fluffy, submicroscopic particulate silica prepared in a hot gaseous environment (2000° F (1100° C)) by the vapor phase hydrolysis of silicon tetrachloride. The average size of primary particles of colloidal silica ranges between 150 and 200 Å.

Silica aerogel is prepared from a gel in which water is replaced with an alcohol. The alcohol is subsequently removed, leaving a skeleton submicroscopic structure which is retained as the solid is ground to powder. These materials have been mixed with fine metallic powders or flakes (such as copper and aluminum) and carbon.

Preheating permits the efficient removal of adsorbed gases and particularly moisture. After preheating, fine powders are effective absorbers of reduced residual gases; therefore, their exposure to the atmosphere should be minimized prior to use.

For any given particle shape, a specific packing configuration will yield a maximum density. For spheres, closest packing occurs

with a rhombohedral arrangement in which each sphere has 12 points of contact. In actual lattices obtained by prolonged shaking of spherical particles, the voids account for about 39.5 percent of the volume, characteristic of orthorhombic or eight-point packing, which yields the highest density that can be practically achieved.

The choice of particle size to obtain a desired density and to prevent compaction under a load, particularly when evacuated powders may be subjected to atmospheric-pressure loading, must be carefully considered. In double-walled pressure vessels, the powder has to be vibrated to settle particles to a density sufficiently high to prevent formation of voids in the insulated space during operation. Filters with extended surfaces, such as perforated tubes wrapped with several layers of fine glass fiber, are required to prevent small particles from clogging evacuation ports or entering the vacuum pumps.

Fibers

In most thermal insulation applications where vibration and shock are expected, fibers have distinct advantages. For cryogenic applications, submicron-diameter glass fibers have been widely used. Very similar considerations govern the use of both powder and fiber insulations. When fibers are used as spacers for multilayer insulations, to reduce the possibility of outgassing, they are prepared without any binders or lubricants. Fibers with low-vapor-pressure binders have been used as supports to space an inner vessel from an outer shell. To insure that multilayer insulations interposed between them are not subjected to compressive loads, such supports have been designed to take acceleration loads.

Composite Insulations

The optimum insulation system should combine maximum insulation effectiveness, minimum weight, and ease of fabrication. It would be desirable to use only one insulation material, but, since no single insulation material has all the desirable physical and strength characteristics required in many applications, composite insulations have been developed. These composite insulations represent a compromise between thermal effectiveness, handling properties, and adequate service life (ref. 25). For cryogenic applications, composite insulations consist of a polyurethane foam; reinforcement for the foam to provide adequate compressive strength; adhesives for sealing and securing the

foam to a tank; enclosures to prevent damage to the foam from mechanical contact, vibration, and aerodynamic heating; and vapor barriers to maintain a separation between the foam and atmospheric gases.

Honeycomb-Foam Insulation

Several external insulation systems use honeycomb structures. Phenolic resin-reinforced fiber-glass-cloth honeycomb is most commonly used. The honeycomb is bonded to the tank with a suitable seal, and a vapor barrier is applied to the exterior of the honeycomb (ref. 26). In such a system, the cells in the honeycomb can be interconnected and evacuated through external pumping, interconnected and purged with helium, or sealed and allowed to reach a low pressure within the sealed cells when the tank is filled with a cryogenic liquid.

Foam-filled honeycomb

The effectiveness of a honeycomb insulation can be considerably improved if its cells are filled with a low-density polyurethane foam. Several techniques have been used for preparing foam-filled honeycomb (ref. 45). For example, the liquid components can be foamed in place to fill the honeycomb cells. This system has not proved effective, however, because of large waste, nonuniform cell structure in the foam, and nonuniform filling of the honeycomb cells. The most common method of preparing foam-filled honeycomb is to press the rigid, phenolic resin-reinforced fiber-glass honeycomb into a preformed sheet of low-density foam. The thin honeycomb walls cleanly cut through the foam so that it fills each cell. However, the foam is not sealed or bonded into the cells; it simply lies within them. This lack of bonding has certain disadvantages because atmospheric gases or helium can diffuse through the insulation. In this, as in other honeycomb insulations, the honeycomb provides compressive strength and allows the insulation to absorb stresses created by differential expansion between the insulating materials and the tank during chilldown. A sealed foam-filled system, however, is not completely reliable. Therefore, a helium-purged, externally sealed honeycomb system was developed for the Saturn S–II insulation system.

The Saturn S–II insulation system

The S–II booster is the second stage of the Saturn C–5 launch vehicle. Overall, it is 33 feet in diameter and 85 feet long. The

liquid-hydrogen tank occupies the largest portion of the second stage's volume. The total insulated tank area is 6000 ft² exclusive of the bulkhead which is common to the liquid-hydrogen and liquid-oxygen tanks. In addition to limiting heat flow during launch and preload, the insulation was designed to be self-snuffing when ignited, to prevent significant air condensation in the insulation, and to provide a means for identifying structural flaws in the tank during fabrication.

The insulation system consists of a foam-filled honeycomb having an overall thickness of 1.6 inches on the tank side wall and 0.5 inch on the bulkhead. The foam is a 2.2-lb/ft³ (0.035-g/cm³) density open-cell polyurethane which is pressed into the honeycomb. This composite is bonded to the tank wall with an adhesive. The vapor barrier on the warm side of the insulation is made up of a nylon-phenolic laminate impregnated with a 0.0015-inch (38.1 microns) seal coating of polyvinyl fluoride, as shown in figure 41. The cold side of the insulation is grooved to provide gas flow channels for helium-purging the insulation during prelaunch and for evacuating the insulation during launch. The weight of the composite 1.6-inch-thick insulation structure is about 0.85 lb/ft² (4.15 kg/m²).

The cylindrical section of the tank is made up of quadrant sections 27 feet by about 9-feet high which are welded into rings. The rings are welded together vertically. The insulation slab is applied to the quadrant sections except at the panel edges, where it is recessed from the weld areas to permit clearance for the weld tools and separation from the heat-affected zone. After the
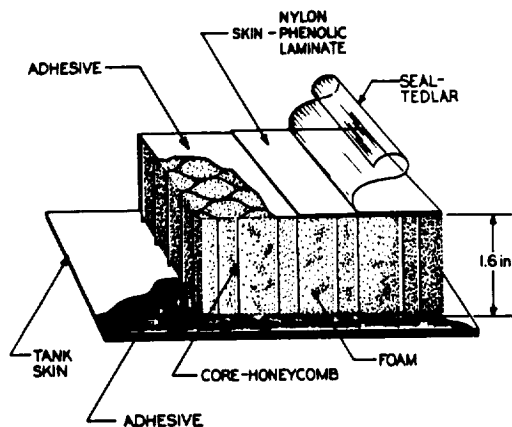
FIGURE 41.—Saturn S-II basic insulation configuration.

tank fabrication and hydrostatic tests are complete, the gaps between insulation panels are filled with foam sections and bonded over with room-temperature-curing adhesives. The manufacturing process is depicted in figure 42.

Results of full-scale tests of the insulation system have not yet been reported; the available performance data have been obtained in subscale tests. These tests included a $\frac{1}{16}$-scale tank and a guarded tank. Thermal conductivity values between 0.6 and 0.75 Btu-in./hr-ft²-°F (0.86 and 1.1 mW/cm-°C) were obtained for the helium-purged insulation at a mean temperature of −200° F (−129° C). A comparison of the results is presented in figure 43. The measured foam conductivities are comparable to the thermal conductivity of helium.

Evaluation of purged honeycomb-foam insulation indicated that the foam was not fully effective because in reducing thermal conductivity the composite insulation rapidly reached the thermal conductivity of the helium purge gas (ref. 45). To improve the insulation effectiveness, the foam was cut to the proper size by pressing it into a slice of honeycomb. The foam was then punched out and each piece of foam was sealed with a polyurethane resin and reinserted into the honeycomb cell. However, the
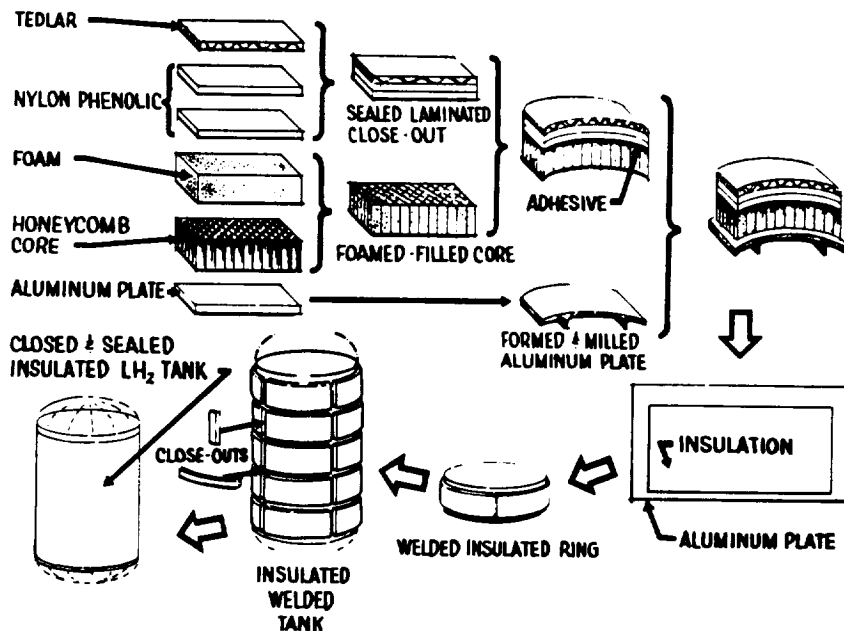
FIGURE 42.—Saturn S–II insulation system manufacturing process.
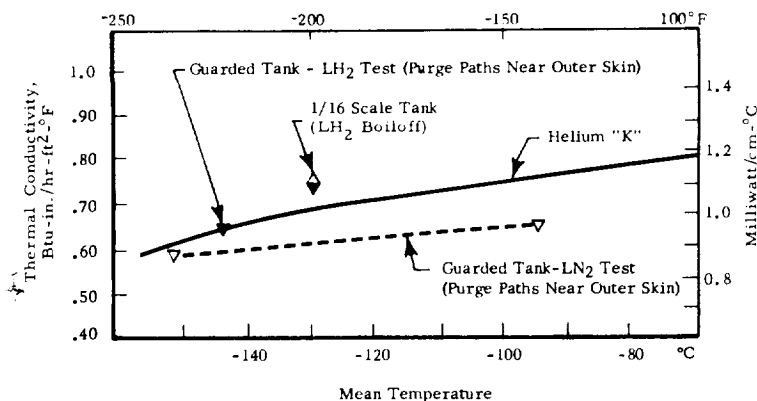
FIGURE 43.—Thermal conductivity of helium-purged insulation
(1.5-in.-thick insulation).

thermal conductivity of the insulation containing the individually
coated foam pieces was the same as if the pieces had not been
coated, indicating that helium readily permeated the sealing
resin. Composite insulation, which is first purged with helium
and then evacuated, was also considered. However, if the vapor
barrier is not leakproof, air can leak into the cold-evacuated in-
sulation and condense.

In addition to the basic hexagonal-core honeycomb, modified
honeycombs filled with rigid urethane foam have been evaluated
for use in insulation systems (ref. 53).

Sealed Evacuated Honeycomb Insulations

One concept considered for a cryogenic insulation was a sealed
honeycomb in which the residual air in the individual cells was
condensed to provide a vacuum in each cell. A removable bag of
lightweight polyester film was to be placed around the exterior
of the insulation to permit a helium purge and to prevent diffu-
sion of air into the insulation in the event of any leaks in the
outer seal. This outer bag was to fall away just prior to vehicle
liftoff. This concept was not tried because an outer bag suffi-
ciently reliable to withstand wind and mechanical loading and
other ground hazards and capable of being removed rapidly from
the vehicle was not found.

A double-seal honeycomb insulation which incorporates a he-
lium-purged layer and a dual layer of honeycomb has been devel-
oped (ref. 54). The layer of the double-seal insulation next to the
liquid-hydrogen tank is made of $\frac{3}{8}$-inch cell polyester honeycomb

to which is bonded a 0.002-inch (50.8 microns) polyester film on the tank side and a 0.0015-inch (38.1 microns) aluminum foil on the outer side. In this layer, each cell is completely sealed; when the layer is chilled to liquid-hydrogen temperature, each cell is evacuated by liquefaction and/or solidification of the gases within it. Thus, the layer provides very effective thermal insulation. The outer layer of the insulation consists of a 3/8-inch cell perforated phenolic honeycomb, 0.2 inch thick, bonded to the 0.0015-inch aluminum foil on the outer side of the polyester honeycomb. The outer surface consists of a 0.003-inch (76.2 microns) aluminum foil bonded to the perforated phenolic honeycomb with an epoxy-phenolic adhesive. In use, the perforated phenolic honeycomb is purged with helium under positive pressure to provide a complete encasement of the polyester honeycomb in a helium envelope. This prevents any possibility of air diffusing into the polyester honeycomb portion of the insulation. If the outer skin is punctured, helium will escape through the puncture. If both seals are punctured, the cell or cells of the polyester honeycomb in the punctured area will fill with helium and helium will escape through the breach in the outer seal so that air is still excluded and the loss in insulation effectiveness is limited to those few cells of the polyester honeycomb that have become helium filled. The double-seal-insulation concept is shown in figure 44. This double-seal insulation weighs about 0.5 lb/ft² (2.44 kg/m²) and has a conductance of 0.3 Btu-in./hr-ft²-°F (0.43 mW/cm-°C).
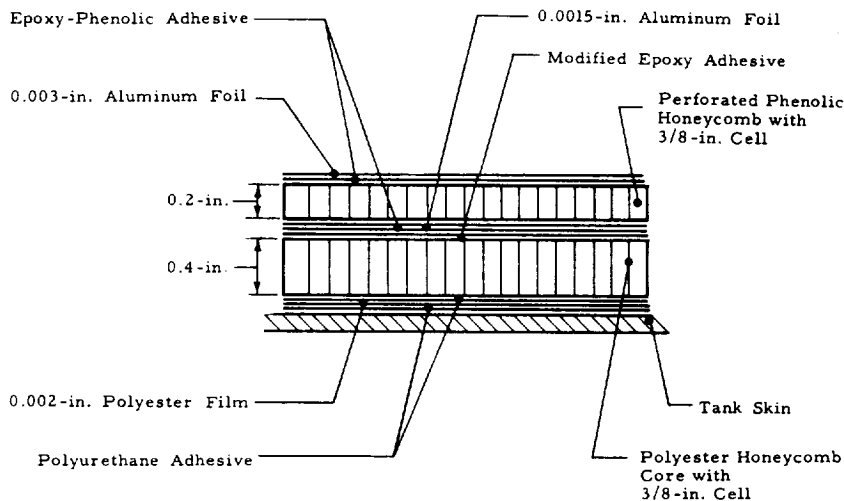
FIGURE 44.—Double-seal insulation.

Composite Insulations for Nonmetallic Tanks

Cryogenic tanks of substantially higher strength/weight ratios than those available have been considered (ref. 55). In such developments nonmetallic materials, such as fiberglass-reinforced plastics, carbon- and graphite-reinforced plastics, and whisker-reinforced plastics, appear to have high potential. If successful tanks are developed using any of these materials, requirements of thermal insulation systems may change substantially. The inherently lower thermal conductivity of reinforced-plastic components compared to that of metals will reduce the insulation requirements. However, the advantages of high strength/weight ratio and low thermal conductivity are offset by the fact that such materials, particularly after thermal cycling, tend to be permeable to cryogenic liquids, thus increasing the need for effective vapor barriers between the liquid and the tank wall as well as between the outside air and the tank and/or insulation. Thus, for reinforced-plastic tanks, improved insulation systems are necessary. The development of filament-wound tanks in which a urethane-foam insulating layer is incorporated either internally or within the fiber-glass-wound structure indicates the current trend (ref. 43).

Constrictive-Wrap External Insulation

An alternative insulation system designed for the Centaur liquid hydrogen-fueled stage consists of a layer of foam to which a vapor barrier and a compression-type surface winding are applied. Using reinforced-plastic filament-winding techniques, the sealed foam constrictive-wrap external insulation system was developed (ref. 56). The constrictive-wrap system consists of 0.4-inch thick (2-lb/ft³ (0.032-g/cm³)) polyurethane foam sealed hermetically with polyester adhesive to a vapor barrier of a Mylar-aluminum–Mylar-sandwich and then overwrapped with a prestressed fiber-glass roving for holding the insulation in place under aerodynamic conditions. Investigations of this insulation indicated that the hazards resulting from impacting insulation panels containing oxygen-rich liquefied air were negligible. The insulation effectiveness proved to be equal to that predicted for the system and the installed weight was only 0.16 lb/ft² (078 kg/m²).

The primary advantages of the constrictive-wrap sealed external insulation system are:

● The self-contained insulation system does not require helium purging or venting.

- It has a low thermal conductivity.
- It is light and therefore need not be jettisoned in flight.

The primary disadvantages of the system are:

- The lightweight insulation is fragile and must be suitably protected during ground handling.
- It may incur weight penalties if atmospheric constituents penetrate and condense in the insulation through any breaches of the vapor barrier.
- As a nonjettisonable insulation it has a payload weight penalty.

Exterior Surface Bonded Foam

The constrictive wrap prevents cracking and delamination of foams subjected to low temperatures on the surface of cryogenic tanks. An alternative approach uses the excellent bonding strength of urethane foamed directly onto the tank surface (ref. 30). With appropriate temperature control (approximately 120° F (50° C)) at the tank wall, the foam can be made with a uniform density. The foam contains chopped strands of fiber glass which provide sufficient reinforcement to prevent it from cracking and delaminating when cold shocked in liquid nitrogen, liquid hydrogen, or liquid helium.

The foam formulation is based on a quadral-triol mix combined with an isocyanate. It is fluorocarbon blown and has a density of 4.0 lb/ft³ (0.064 g/cm³). The initial mix when combined with the chopped fiber-glass strands has sufficiently low viscosity to allow the foaming action to proceed to a uniform density. The chopped glass strands have a random orientation and provide strength to the foam in all directions.

The foam system was applied to a tank 4 feet in diameter and 27 inches deep. Foaming was accomplished in orange-peel segments approximately 6 inches wide in a ½-inch space formed by the tank wall and a plastic form. (See figure 45.) Both the tank and foam were maintained at a temperature of approximately 120° F (50° C). The outer surface of the foam had the same smooth surface as the form. When the foaming was complete, a vapor barrier of polyester-aluminum laminate was attached to the outer surface with a polyurethane adhesive. The joints in the vapor barrier were sealed with pressure-sensitive tape. The completely insulated tank is shown in figure 46.

Tests were performed with this insulation to measure thermal performance and to determine structure resistance to cold shock. The heat flux through the insulation was measured with liquid

Figure 45.—Foam-insulation molding die and fixture.

hydrogen and liquid nitrogen in the tank, and the tank exposed to the atmospheric environment. The measured heat flux ranged from 70 to 100 Btu/hr-ft^2 (22 to 32 mW/cm^2). The average thermal conductivity was computed to be 0.13 Btu-in./hr-ft^2-°F (0.19 mW/cm-°C). The outer surface temperature ranged from $-60°$ to $+62°$ F ($-51°$ to $+17°$ C), which is above the condensation temperature of air.

Repeated filling of the tank with liquid hydrogen and liquid nitrogen and spraying the outside of the insulation with liquid nitrogen while the tank was filled with liquid hydrogen did not impair the thermal performance of the insulation. It retained structural integrity except for minor liftoff of the vapor barrier.

Another application of external foam on an aluminum liquid-hydrogen tank showed good results (ref. 26). The insulation was bonded to the tank with an intermediate layer of epoxy-coated fiber-glass cloth. The adhesive qualities were best only when the aluminum surface had been precleaned and vapor blasted.
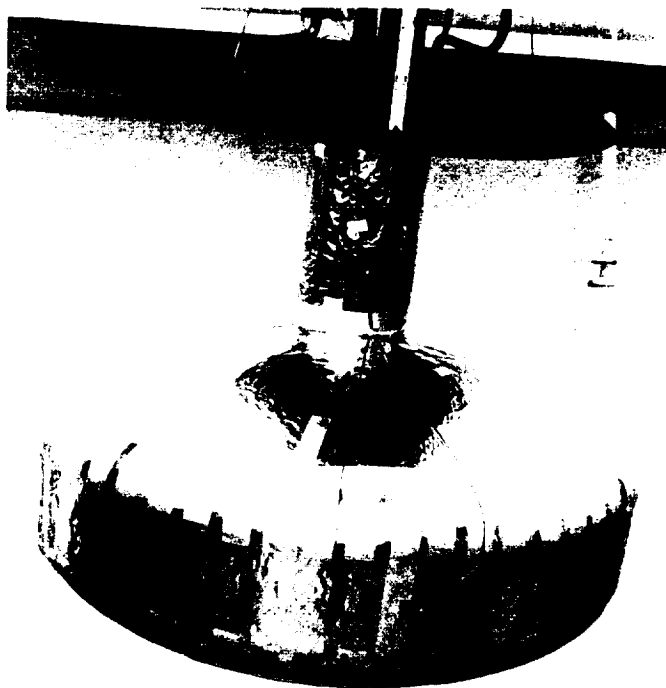
FIGURE 46.—Foam-insulation system with vapor barrier.

Internally Insulated Fiber-glass Cryogenic Storage Tank

Plastic foams and glass-filament-wound structures can be combined to produce a lightweight liquid-hydrogen tank. (See ch. 4, p. 81.) This approach was used on a tank of 40-gallon capacity, 18 inches in diameter by 36 inches long, designed to operate at 100 psig. (See ref. 56.) A layer of foam ½-in. thick is used as the mandrel for the filament winding operation. A vapor barrier is placed on the interior of the foam structure to make the tank capable of containing gaseous and liquid hydrogen. (See ch. 5.)

The foam layer of the tank is made of an upper and lower dome section and a cylindrical section. Each section is formed of polyurethane foam encased in an aluminum-Mylar-aluminum (AMA) laminate which serves as a vacuum tight barrier. A glass cloth is placed between the foam and the AMA laminate to provide a path for gas flow when the foam is evacuated. The foam acts both as a thermal insulation and as a structural material for transmitting the internal pressure to the filament-wound shell structure. Construction details of the foam and

vacuumtight barrier in the vicinity of the joint between the cylinder and dome sections are shown in figure 47.

The structural shell is made up of two layers of longitudinal and four layers of circumferential wraps of glass filaments. The roving consists of 20-end S/HTS fiber glass impregnated with a low-temperature casing epoxy. The completed filament-wound tank is shown in figure 48.
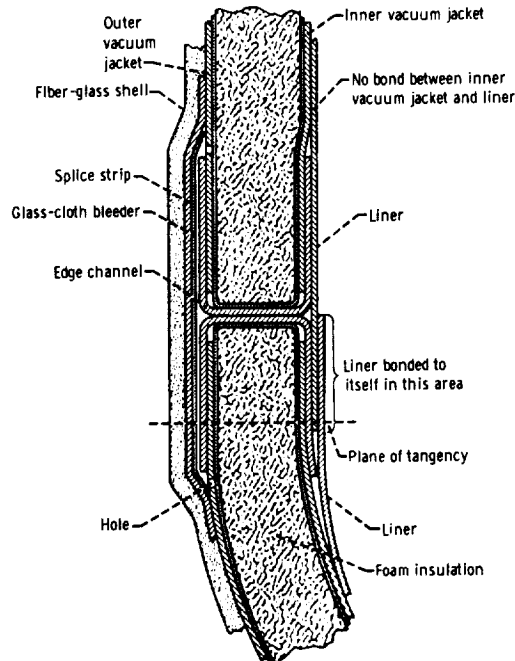
FIGURE 47.—Detail of joint between cylindrical and dome sections of tank foam layer.
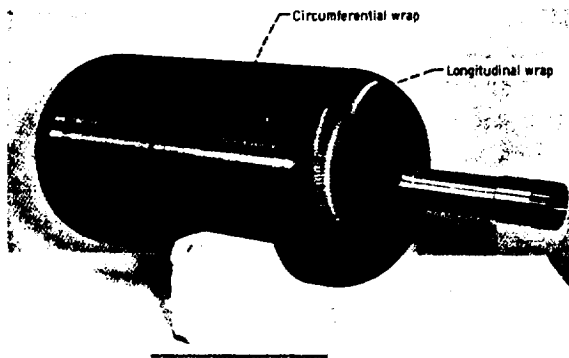
FIGURE 48.—Completed filament-wound test tank.

The liner for the tank was fabricated from AMA laminate. The domes were spin formed from 0.005-inch-thick (127 microns) laminate and the cylinder section from 0.0025-inch-thick (63 microns) laminate. The liner joints were sealed with an adhesive to maintain a hermetic seal at $-423°$ F ($-253°$ C) after curing at a temperature compatible with the foam insulator.

The vacuumtightness of the enclosed foam was checked with a helium mass spectrometer both before and after the tank was coldshocked with liquid nitrogen. The heat flow through the insulation was determined by monitoring the flow rate of vaporized hydrogen with the tank exposed to atmospheric conditions. To test its structural performance, the vessel was pressure cycled while filled with cryogenic liquid.

When the tank was filled to about 75 percent of its volume, the heat leak was about 1800 Btu/hr (530 W); that is, a 50-percent liquid loss per hour. A significant portion of the loss, about 1100 Btu (1160 kW-hr), was attributed to the conductive heat flow in the AMA laminate at the joint between the bottom dome and cylinder sections in the foam structure (fig. 47). Depending on the environmental conditions, the heat flux in the cylindrical section was 80 to 110 Btu/hr-ft² (25.2 to 34.6 mW/cm²), corresponding to a thermal conductivity of the foam of about 0.1 Btu-in./hr-ft²-°F (0.144 mW/cm-°C).

The liner of the vessel failed at an internal pressure of 68 psig after successful performance at lower pressures. Failure was attributed to overstressing of the liner material.

Self-Sealing

Meteoroid particles impacting cryogenic propellant tanks will not only penetrate the tank wall but may also generate forces that could cause catastrophic failure of the tank. External thermal shielding and insulating systems for the tanks can be designed to incorporate an exterior meteoroid bumper together with a low-density energy-absorbing material between the bumper and the tank wall to provide meteoroid protection. Attention has been given to using structures similar to sealed exterior insulations as self-sealing shields for micrometeorite protection (ref. 57). If a cryogenic propellant tank is penetrated by a micrometeorite, the cryogenic propellant will solidify when it encounters the vacuum of space. If there is a porous medium around the penetration, the solidifying propellant will cling to this medium and plug the hole. Tests were made by filling a honeycomb with porous media, such as fiber glass and an open-cell polyester foam.

The most favorable self-sealing results were obtained with the open-cell polyester foam, which produced sealing of punctures as large as 0.050 inch in diameter.

Other Materials

A large number of other materials have been screened as possible candidates. Those which have proved useful are corkboard and balsa wood (ref. 59). Although balsa wood is a good nonporous insulator, it is brittle and difficult to fabricate into thin sections. Corkboard is readily available and relatively nonporous (ref. 58); it has a low conductivity, but a high density which limits its use for space vehicles. Corkboard tends to separate and crack near the tank walls during cooldown. Like balsa, it is difficult to fabricate in curved sections.

Structural and Noninsulating Cryogenic System Components

ATTACHMENTS AND SUPPORTS

Insulation Attachment Methods—Multilayer Insulations

Since multilayer insulations consist of separate layers, methods must be devised to apply insulations on vertical and inclined walls so that the insulation will not slip during fabrication and assembly or as a result of shock and vibration during use.

Insulation Supported Between Two Structures

The simplest way to prevent a multilayer insulation from moving or slipping is to place it over the object to be insulated and to contain the insulation by a tight outer shell. This method, however, has several drawbacks:

● Since the performance of the multilayer insulation is very sensitive to compressive load, the outer shell can exert only a limited amount of pressure, and the frictional force developed between the layers as the result of this force may, in many cases, not be enough to keep the layers in place.

● Even a small amount of compression degrades the insulation effectiveness.

● Narrow tolerances must be maintained in manufacturing the outer shell.

● The design is too inflexible to permit small corrections which may be necessary for final adjustments.

● Compressive loads may be developed because of differential thermal expansion of the inner colder layers and the outer shell. The difficulties can be overcome by enclosing the insulation with an outer flexible screen. During assembly, the bag can be pulled tighter or looser as required.

An alternative approach uses each spacer as a self-supporting shell for its radiation shield. Such an assembly is more difficult to prepare, but the insulation can withstand rough handling and vibration more easily. Figure 49 shows an example of an insulation using this approach.
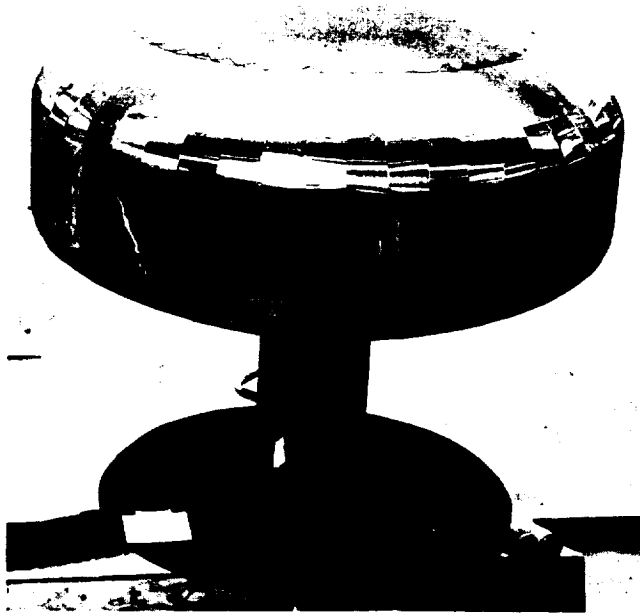
FIGURE 49.—Insulation assembly using spacers as self-supporting shells for radiation shields.

Pinned and Quilted Insulation

Layers of a multilayer insulation can be pinned to the wall of the object to be insulated (fig. 50) or they can be stitched or quilted together into a blanket (refs. 18, 30, 59), which can then be attached to the tank in individual sections (fig. 51). If no external compression is applied to the insulation, the performance of the pinned or quilted blanket can be estimated from the data on penetration presented in chapter 5 and confirmed by test.

Experimental data on a quilted insulation consisting of ten radiation shields of 0.00025-inch-thick (6.3 microns) perforated polyester film, aluminum coated on both sides, and eleven 0.003-inch-thick (76 microns) silk nettings (with 1/4-inch-diameter by 0.008-inch-thick (200 microns) glass-paper disks sewed on both sides of silk netting on 1-1/2-inch centers with 0.006-inch-diameter (150 microns) thread (fig. 25), indicated that the quilting degraded the performance by 7 percent (ref. 30).

A quilted blanket insulation combined with a purgeable substrate system was tested on a one-half (linear) scale model of a Saturn V, Apollo-landing-module liquid-hydrogen storage tank

FIGURE 50.—Multilayer insulation pinned on the tank wall.
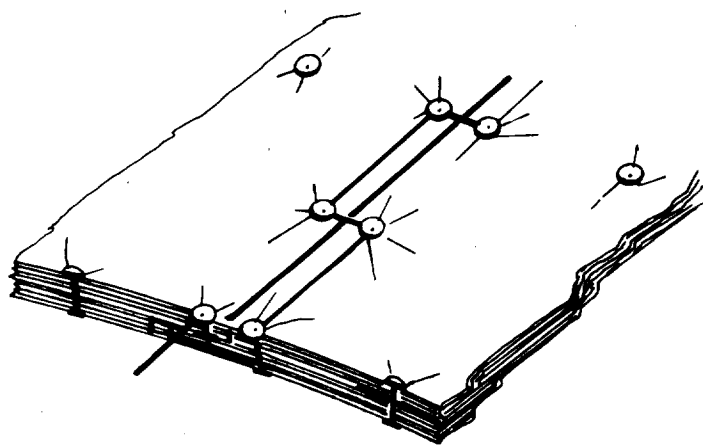
FIGURE 51.—Quilted insulation.
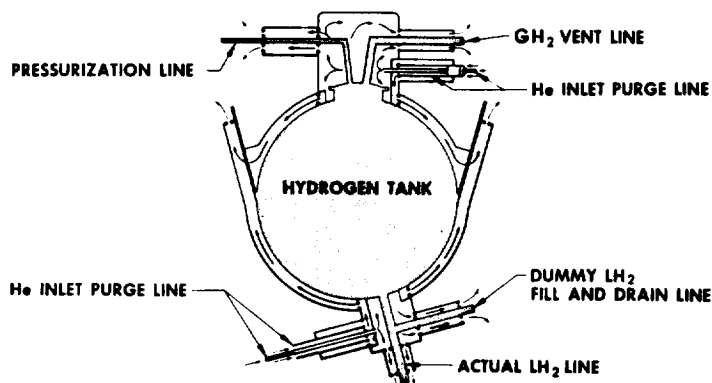
FIGURE 52.—Schematic of helium-purge substrate system.

(ref. 18). The quilted blanket insulation system was chosen because it can function satisfactorily during prelaunch ground hold, launch, and prolonged space flight. The spherical tank, about 82 inches in diameter, was provided with fill, vent, pressurization, and drain lines.

The insulation system consists of several layers. First, a 0.4-inch-thick fiber-glass substrate layer was placed over the tank and enclosed by a gastight bag. This layer can be purged with helium during prelaunch ground hold. (Fig. 52 shows the arrangement of the helium-purge system for the test tank.)

The insulation consists of 30 radiation shields of double aluminized polyester film, 0.0025 inch thick (63 microns), separated by 0.0028-inch (71 microns) glass-paper spacers, combined into blankets, each consisting of 10 shields and 9 spacers. The layers are held together with buttoned tie-throughs to form a quilted blanket. The blankets are in modular sections and completely cover the tank. Three blankets are placed over each other to build up the insulation system to the required number of layers. The separate blankets are held together with Velcro fasteners interspersed between the blanket at appropriate intervals. A polyester netting is placed over the outer blanket to provide additional strength to the system. The details of this system are shown in figure 53.

Bands

When large objects are to be insulated with multilayer insulations, bands can be used to keep the insulation in place (fig. 54). Bands apply compression to a relatively small portion of the total

Dacron Netting Outer Sheath

Alternate Layers of Double Aluminized Mylar and Dexiglas Spacers

Buttons

Single Button Blanket

Velcro Fasteners

Press to Fasten, Peel to Remove, (Fasteners are Reusable)

Hook

Pile

Matching Parts of Velcro Fasteners

Velcro Attachment Tank Wall Substrate and Blankets 1 to 2 and 2 to 3

Mylar Tabs

Aclar Purge Bag

Tank Wall Cross-Section of Three Installed Button Blankets

Structure

Staggered Butt Joints

Helium-Purged Fiber-Glass Batting Substrate

FIGURE 53.—Quilted blanket insulation.

Spacers

Tank

Radiation Shield
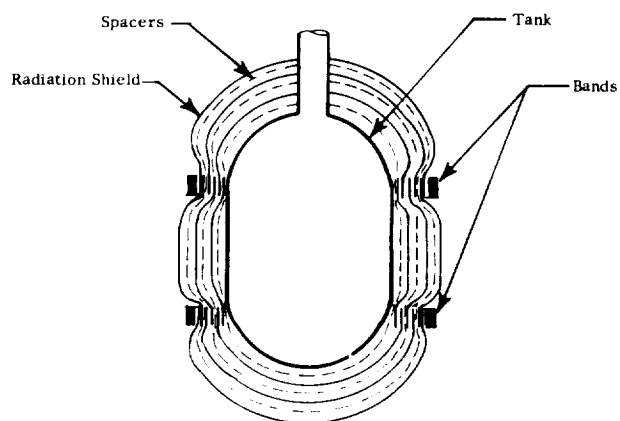
Bands

FIGURE 54.—A multilayer insulation kept in place by bands.

surface area of the insulation. For radiation shields that are poor heat conductors in the plane parallel to their surface (such as thin plastic shields), the adverse effect of compression on the thermal performance is localized. The local effect of the band can be estimated according to the discussion in chapter 4, page 49. Compressive loads and affected areas can be estimated, and then the heat loss can be added to the heat flux through the unaffected areas.

Shingled Insulations

The shingled multilayer insulations (fig. 55) derive their name from their similarity to roofing shingles (ref. 60). One end of each shingle is attached to the tank wall (or substrate insulation) overlapping an adjacent shingle. The length of the shingle from the attachment point to the outer edge and the spacing between shingles at the bonded edge determine the number of layers that can be applied. The shingle insulation has the following advantages:

● The multilayer insulation can be directly attached to the tank wall.

● Gas trapped between the shingles can be rapidly vented.

● Gas from any point source of gas leak such as the tank surface at weld areas and manhole covers will be trapped between two shingles and vented to space before it can permeate the outer layers.

SHINGLE

BUTTON

PROPELLANT SIDE   TAPE
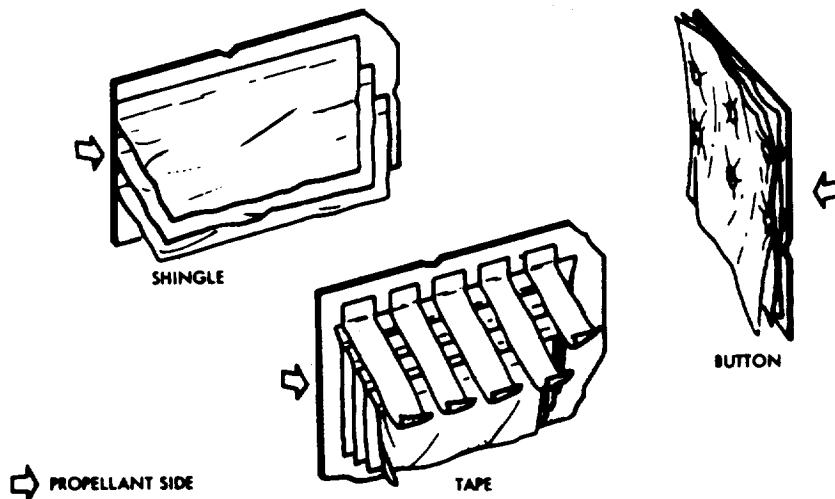
FIGURE 55.—Shingled multilayer insulation attachment methods.

Loss in insulation effectiveness due to solid conduction along the shingles, and radiation tunneling between adjacent shingles, can be reduced by choosing a shingle of suitable length.

The total heat flux is approximately the sum of heat passed across the insulation plus radiation tunneling plus the solid conduction along the shield. The sum of the radiation tunneling and solid conduction along the shield represents the thermal degradation due to the shingle configuration over and above the thermal conductivity for the parallel layers. As shingle length increases the thermal conductivity of the shingled multilayer, insulation asymptotically approaches a value equivalent to parallel multilayer insulation. For shingle lengths greater than 28 inches, the thermal degradation is less than 40 percent of the thermal conductivity of parallel multilayer insulation.

Figure 56 shows the effects of gas leakage on the performance of shingle insulation. For comparison, the data for a multilayer system with parallel button radiation shield is shown on the same figure. The results indicate that the performance of the shingle insulation is nearly insensitive to gas leaks when the shingles are vented to the vacuum without permeating the outer layers; the performance of one shingle layer is degraded in the immediate vicinity of the gas leak.
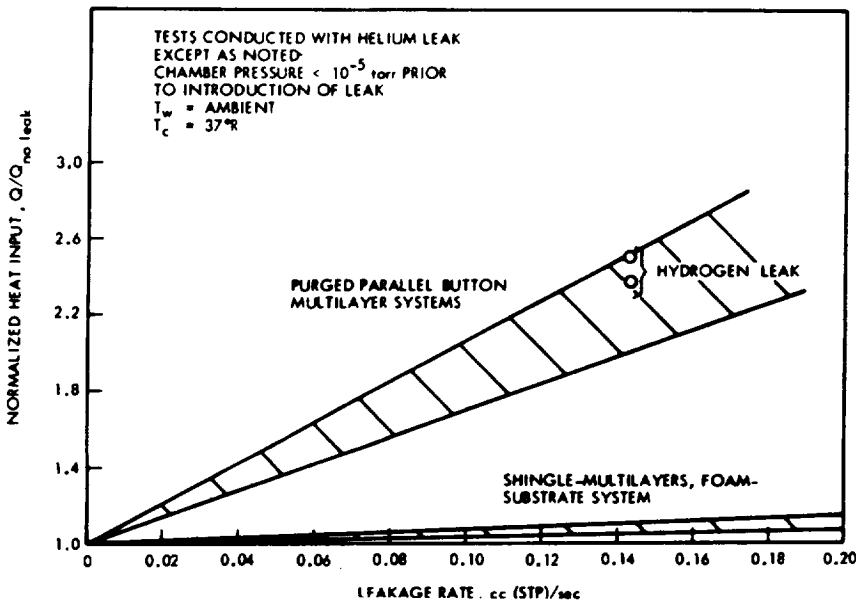
FIGURE 56.—Normalized heat input through multilayer systems as a function of point source leakage rate.

The performance of shingle insulation was tested on a 4-inch-diameter, 100-inch-long calorimeter as well as on a 26-inch-diameter test tank with hemispherical ends. The test included exposure to thermal shock, that is, rapid cooldown from ambient to 37° R (20° K) with no prechill, rapid pumpdown (0.2 psi/sec), vibration in longitudinal and horizontal planes, acoustic load (to 158 dB), and acceleration up to 20 g. No structural damage to the shingles or significant change in insulation performance occurred during these tests.

Structural Supports

The support requirements for an insulated object or a tank depend on its projected application: laboratory equipment will be handled more gently than over-the-road or field equipment, which will be subject to accelerations and vibrations around all three axes. The supports for the latter conditions have to be of greater strength and therefore more massive than the supports for laboratory equipment. Various materials and design approaches for the support structures have been developed to suit load conditions and to minimize heat losses in cryogenic storage tanks ranging from road-transportable tanks to tanks in small electronic devices.

Materials

Thermal conductivity, tensile strength, and modulus of elasticity are the most significant design properties for a support system. A number of suitable structural materials are listed in table 6 along with values for each property.

The heat leak per unit of load for a support member in pure tension is proportional to k/σ, where k is the thermal conductivity and σ is the maximum working stress of the member. Using room-temperature values of the conductivity and stress, table 6 shows the k/σ ratio for several materials. Among these materials, the industrial yarns—Dacron, Nomex, and glass fibers—have significantly lower values of k/σ than do stainless steels and the titanium alloys. Thus, on this basis alone, the yarns are promising for support materials. However, other factors, such as the percent elongation at the maximum loads and the temperature coefficient of expansion, must also be considered in the design of support systems.

The natural frequency of the support systems must be greater than the frequency of any excitations that result from the vibrations and accelerations induced by handling or transportation. The criteria for determining whether a material will give a mini-

mum conductance support for a given system natural frequency (tension support) is to have a minimum ratio of the thermal conductivity of the support to its modulus of elasticity, k/E. Table 6 shows the value of this ratio for various materials; again, it is apparent that the synthetic yarns—Dacron, Nomex, and glass fibers—are among the best.

Tension Supports

Two examples of the tension type of support are shown in figure 57. Each system requires six tension members. In one system (fig. 57(a)), each set of three structural members connects to a rigid or cantilevered support that penetrates the insulation. In the other system (fig. 57(b)), each structural member connects to the tank at a different location and each, therefore, penetrates the insulation separately. Analysis of the effects of vibration
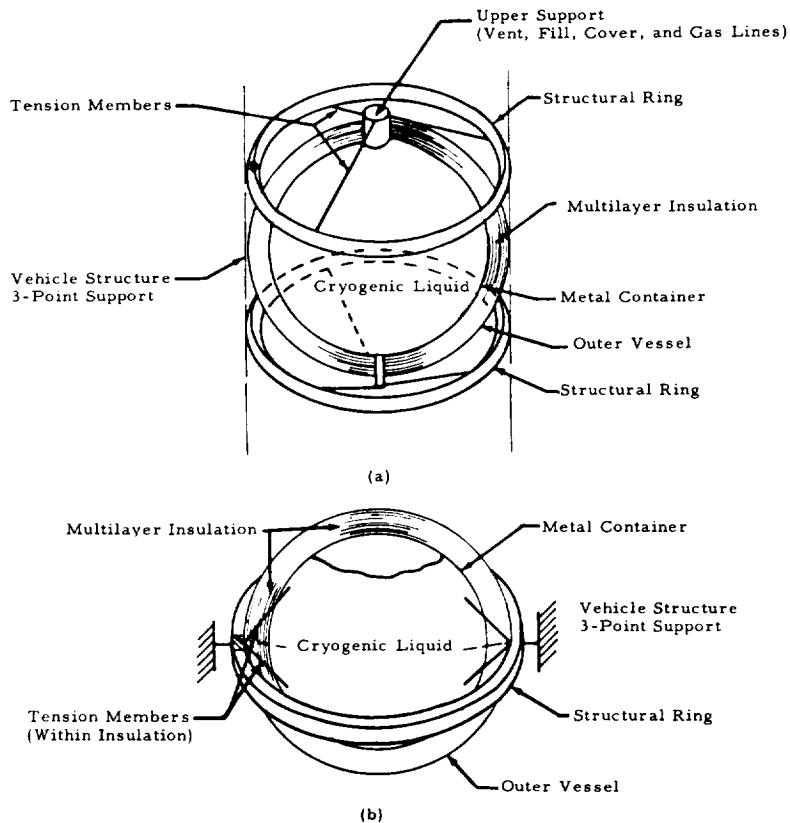
FIGURE 57.—Tension-support systems for cryogenic containers.

TABLE 6.—*Thermal and Mechanical Properties of Support Materials*

	Modulus of elasticity		Thermal conductivity		Tensile strength		Thermal conductivity/Tensile strength		Thermal conductivity/Modulus of elasticity	
	psi (×10⁶)	kg/cm² (×10⁵)	Btu-in. / hr-ft²-°F.	mW/ cm-°C.	psi (×10³)	kg/cm² (×10³)	Btu-in.³ / hr-°F.-ft²-lb (×10⁻⁴)	mW-cm / kg-°C. (×10⁻⁴)	Btu-in.³ / hr-°F.-ft²-lb (W10⁻⁶)	mW-cm / kg-°C. (×10⁻⁶)
Stainless steel	29	2.0	98	140	90–280	6.1–19.4	11 –3.4	230 –70	3.4	72
Titanium alloy (7 percent Al, 4 percent Mo)	17	1.2	49	70	60–170	4.1–11.6	8.2–2.9	170 –60	2.9	61
Pyroceram (9608)	12	.85	14	20					1.12	24
Borosilicate glass	9.1	.62	7.8	11					8.6	18
Wood:										
Balsa	.5	.03	.36	.52					.75	17
Maple	1.8	.12	1.3	1.9					7.2	160
White pine	1.2	.08	1.0	1.4					.83	1200
Industrial yarn:										
Dacron	2.0	.14	1.1	1.6	80–140	5.4– 9.9	0.14–0.07	2.9– 1.6	5.5	11
Nylon	.95	.06	1.7	2.5					1.79	41
Nomex	2.8	.19	.9	1.3	70– 90	4.8– 6.1	0.13–0.10	2.7– 2.1	.32	6.8
Epoxies—cast:										
Unfilled	.35	.02	1.3	1.9					3.7	93
Glass filled	3.0	.20	2.4	3.5					.8	17
Glass fibers	17	1.1	7.2	10	200–220	13.6–15.0	0.36–0.33	7.6– 6.9	.43	9.1

shows that the natural frequency of the tension members is given by

$$f_n = \frac{1}{2\pi}\sqrt{\frac{6k\cos^2\alpha}{M}}$$

where k is the spring constant, α is the angle of the tension member with the vertical, and M is the mass of the container.

Multiple Thermal Resistance Support

This support system makes use of the low thermal conductivity and the high load-carrying capacity of multiple-resistance supports in a vacuum (ref. 61). The supports can be integrated with an inner cryogenic container so that they connect the inner container to the container support structure without transferring loads to the outer shroud.

Two types of supports have been successfully used:

● A conical support, consisting of multiple assemblies of truncated conical washers coated with magnesia powder. Figure 58 shows the assembly of such a support, and figure 59 shows the
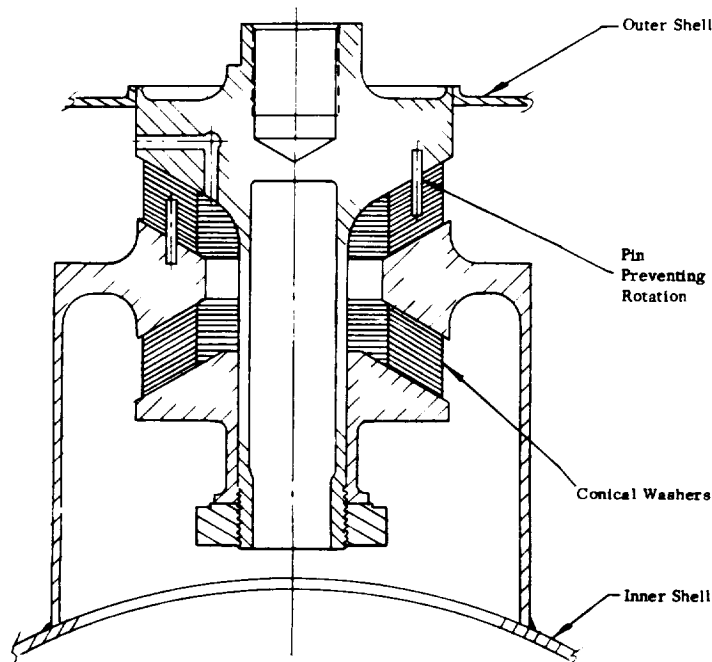
FIGURE 58.—Conical washer support.

FIGURE 59.—Unassembled parts of conical washer support.

unassembled support parts. The conical shape of the washer provides for self-alinement of the washers, capability of carrying loads normal as well as parallel to the axis of the container, and self-compensation for contraction of components of the support when the inner container is filled with a cryogenic fluid.

● A flat support (figure 60), consisting of a spiral-wound metal strip coated with magnesia powder. This support can resist lateral forces only.

The conical support may be assembled and preloaded prior to assembly of the cryogenic container. This assembly is welded to
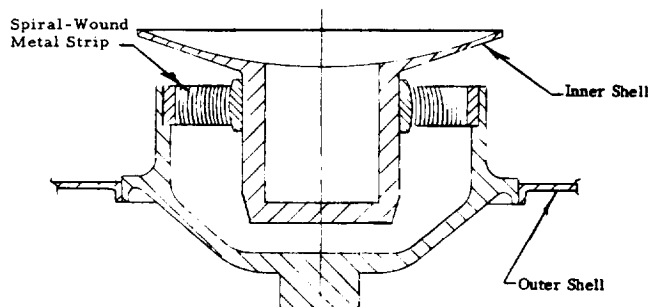
FIGURE 60.—Spiral-wound metal strip support.

a cylindrical section which has been welded to the inner container. When the inner container is assembled inside the outer shroud, a threaded plug can be removed from the bottom support and the axial spacing of the inner and outer container determined and fixed. This plug is later inserted and welded in place. Thus the assembly of the cryogenic container is relatively simple and requires no critical tensioning of supports during final assemblies.

Load-Supporting Insulation

Extensive work on the effects of compressive loads on multilayer insulations has indicated that it is feasible to develop multilayer insulation systems that can support light loads.

A prototype cryogenic container had insulation consisting of aluminized polyester film and fiber-glass spacers. The fiber-glass spacers with a silicone resin binder have a density of 9 lb/ft³ (0.14 g/cm³). Eighty percent of the spacer material was removed and the rest was precompressed to achieve an installed density of 2.8 lb/ft³ (0.04 g/cm³). The insulation system was compressed between the inner container and an outer shroud so that the desired preload was obtained with the inner container at the cryogenic fluid temperature.

Small dynamic loads are carried in shear by the insulation around the circumference farthest from the axis of vibration. Larger dynamic loads are carried by sliding friction around the circumference away from the axis of motion and by compression at the ends of this axis. Coulomb damping in the insulation subjected to shear and hysteresis in the compressed insulation both provide damping to limit the relative motion between the two vessels.

Tests of the prototype container, which consisted of a 29-inch o.d., ¼-inch stainless-steel inner vessel and a 31-inch i.d., 0.070-inch-thick stainless-steel outer vessel, indicated a heat leak corresponding to an apparent thermal conductivity of 0.0042 Btu-in./hr-ft²-°F (0.0060 mW/cm-°C).

Cone Support System

The cone support can be made of various materials; for example, titanium sheet or a polyester honeycomb formed to a cone shape and bonded to a girth ring around the inner container and a girth ring on the outer shroud (ref. 18). The cone can be designed to withstand longitudinal accelerations in two directions as well as transverse accelerations for both the tensile and buckling loads associated with such accelerations.
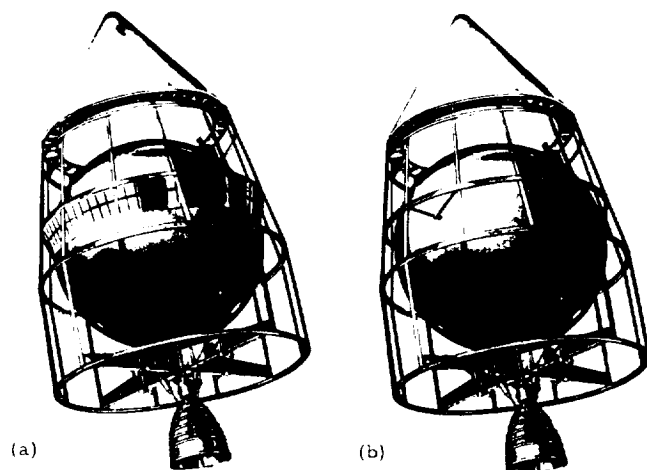
FIGURE 61.—Cone support system concepts. (a) Continuous cone support; (b) three-point support.

Because this type of support penetrates the multilayer insulation, the attachment of the individual layers to the cone must be made in such a way that the temperature of the shields matches the temperature distribution in the cone support. Thus isothermal surfaces can be preserved around the container in the vicinity of the cone support and thermal short circuits prevented. Figure 61 shows the design concept for such a support system.

Refrigerated Supports

The sensible heat of the vaporized liquid can be used to reduce the heat flow conducted through the supports. The vent gas can be made to pass out of the system through small-diameter vent lines which can either be thermally bonded to the support or serve as the supports. The cold boiloff gas is introduced at the support where it attaches to the cryogenic containers. The gas passes outward through the support, warming up as it picks up heat in the support member. A substantial reduction in the support heat leak can be obtained in this manner (ref. 5).

Retracting Supports

Retracting supports are of interest where the insulated tank may go through two modes of operation. For example, during transport, the tank may be exposed to vibration and shock, whereas, in use, it may remain stationary for prolonged periods.

Massive support structures required during transport may be retracted at the final destination, thus decreasing heat losses during stationary operation.

PENETRATIONS

In any practical application, penetrations, such as fill lines and vent lines on a cryogenic tank or electrical leads on electronic equipment, are unavoidable.

Analyses describing the relationship between the penetration and highly anisotropic multilayer insulations have been carried out (ref. 62). Because of the important effect penetrations have on insulation effectiveness, considerable care must be taken in designing the system, selecting materials, and evaluating experimental data obtained on idealized systems.

Buffer Zones in Multilayer Insulations

Multilayer insulations are highly anisotropic; that is, heat flow in a direction parallel to the layers is orders of magnitude greater than the heat flow perpendicular to the layers.

This anisotropy has to be recognized in the design and construction of multilayer insulations whenever there is a penetration or a seam in the insulation. A simple case is illustrated in figure 62(a). Here the multilayer insulation is in good thermal contact with a penetration. Heat flows not only directly through the penetration but also from the multilayers into the penetration; this effectively short-circuits the insulation in this region. The isolation of a penetration (or any other short circuit) by additional, but isotropic, insulation in the space between the penetration and multilayer insulation is known as "decoupling" and the space is referred to as a "buffer zone." The decoupling insulations employed include urethane foams and evacuated glass wool or powders. Foams are rigid and can be produced with accurate geometry. Because of the gas entrapped in the foam pores, the thermal conductivity of foams is generally higher than that of evacuated glass wool or powders. However, the latter insulations are more difficult to install.

For small penetrations, especially those with a low-thermal-conductivity–area product, it may be satisfactory to place the insulation near the penetration but to prevent actual physical contact. These gaps in the insulation must neither widen nor narrow during cooldown or under any anticipated loading.

A large gap through which radiation can reach the insulated object is intolerable in terms of heat leak. Large support members,
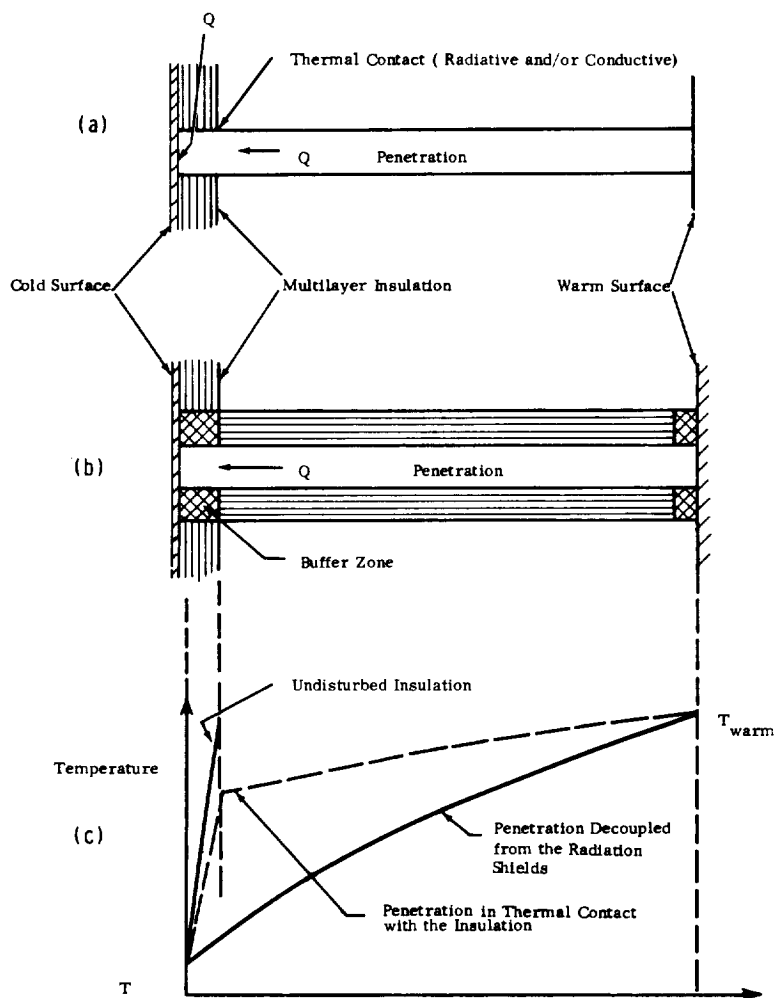
FIGURE 62.—Treatment of a penetration passing through multilayer
insulation.

pipes, and manholes require that the gap be closed with a low-
conductivity isotropic material. In figure 62(b), the penetration
is shown with a decoupling material to prevent the insulation
from contacting the penetration. The temperature gradients for
the penetration system in figures 62(a) and 62(b) are shown in
figure 62(c). The use of a decoupling material and axial insula-
tion around the penetration considerably decreases the heat leak.
When low-thermal-conductivity spacers are used in a multilayer
insulation, the spacer material can also serve as the buffer zone

by continuing the space beyond the radiation shields for a distance equal to about twice the thickness of the multilayer insulation.

In the placement of multilayer insulations on tanks, seams of joints between insulating sections are often encountered. Instead of trying to match layer to layer (figure 63(a)), these seams are often decoupled with another (isotropic) insulation. For example, in figure 63(b), such a decoupling is shown for a right angle turn in the cold wall.

The analyses of heat leaks through a buffer or decoupling zone are difficult and must be confirmed by actual tests. For the case shown in figure 63(b), the heat flux due to the coupling section is $Lk\Delta T$, where L is the length of the joint, k is the thermal conductivity of the decoupling insulation, and ΔT is the difference between the inner and outer temperatures. The dimensions of the square are not significant. Other quantitative analyses are made for various cases (ref. 62).

Penetration Through Multilayer Insulation With Metal-Coated Plastic Shields

The heat loss through a system consisting of a small penetration such as a plastic or stainless-steel pin or thin-wall, stainless-steel tube through a multilayer insulation which has thin metal-coated plastic radiation shields (such as 0.00025-inch-thick (6.3 microns) aluminum-coated polyester film) may be approximated by the sum of heat losses calculated separately for the penetration, multilayer insulation, and buffer zone (ref. 63). This procedure is not exact because no interaction between the penetration, buffer zone, and multilayer insulation is taken into account. However, the method gives a reasonably reliable technique for determining the effect of a penetration, as shown in table 7, which

(a)   (b)
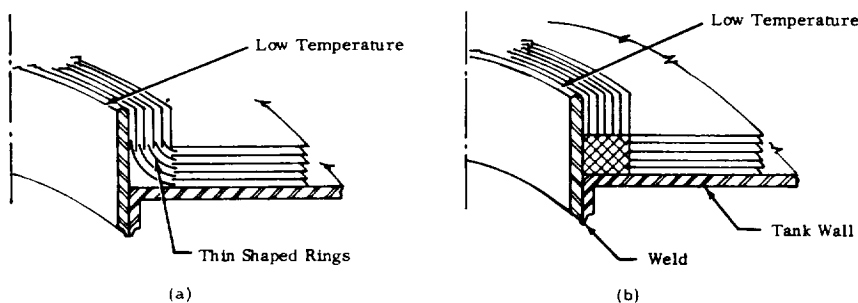
FIGURE 63.—Treatment of joint seams in the placement of multilayer insulations on tanks. (a) Layer-to-layer matching. (b) Decoupling for a right-angle turn.

TABLE 7.—*Comparison of Calculated and Experimental Heat Flows for Penetrated Multilayer Insulation*

Penetration		Buffer zone diameter, in.	Heat flow									
Material	Description		Penetration		Buffer zone		Insulation		Total			
									Calculated		Experimental	
			Btu/hr	mW	Btu/hr	mW	Btu/hr	mW	Btu/hr	mW	Btu/hr	mW
Stainless steel	Pin 0.020 in.	0.25	0.10	29	0.013	4.0	0.017	5.0	0.13	38	0.12	35
		.04	.11	32	<.001	<.3	.017	5.0	.13	37	.12	35
		1.88	.18	53	.24	70	.016	4.7	.44	128	.47	138
Nylon	Pin 0.032 in.	.04	.006	2	<.001	<.3	.046	13	.052	20	.063	18
		.28	.006	2	.003	1.0	.046	13	.055	16	.042	12
Stainless steel	Tube 0.25-in. o.d., 0.001 in. thick.	.28	.25	73	.016	5.0	.046	13	.31	91	.32	94

compares calculated and experimental results. For the test conditions selected, the buffer zone around the penetration has an adverse effect: it adds to the total heat loss through the system.

Use of Vapor Cooling

The design of a refrigerated support employing heat stations (fig. 64) greatly reduces the conductive heat losses down the penetration. A plastic support tube filled with powder or fiber insulation carries the fill (withdrawal) and vent lines and cables which penetrate the insulation. Three equally spaced heat stations in the piping penetration pass transversely through it and are thermally bonded both to the support tube and to all of the pipes. The vent line is coiled and bonded to each of these heat stations so that a transverse isothermal surface is established at each heat station. This surface assures that the specific heat available in the boiloff gases can be used to intercept conductive
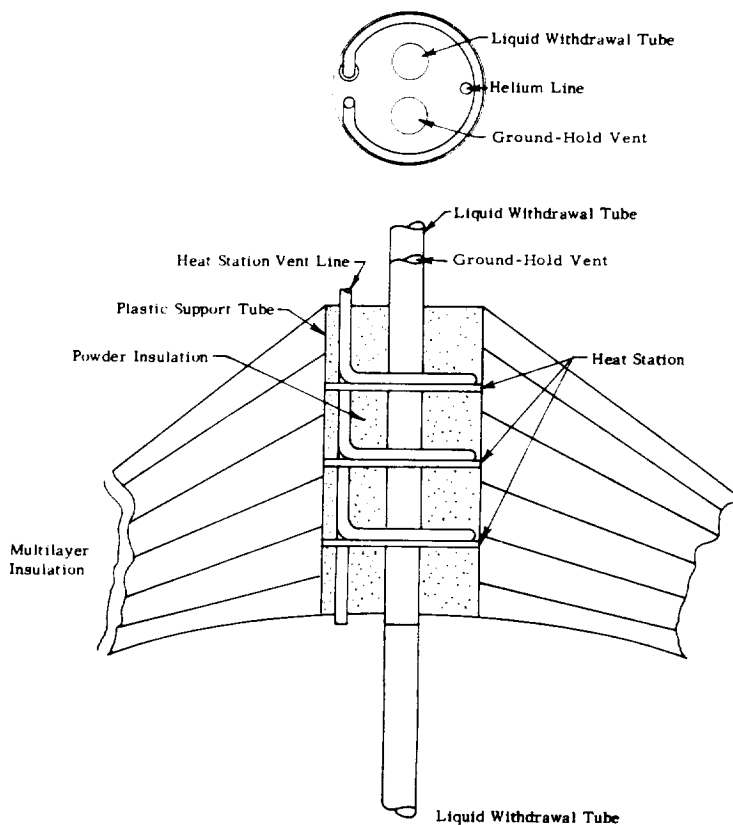
FIGURE 64.—Heat stations for piping penetration.

heat leaks down the pipes and reduce the total flux through this penetration. The multilayer insulation layers are attached to the structural support tube of the piping penetration at a point where the tube temperature matches the shield temperatures. Analysis of heat leak through the piping penetration as a function of a number of heat stations shows that the heat leak, when two heat stations are used, is reduced to 0.1 and for three heat stations, to 0.05 of the heat leak with no heat station (ref. 64).

To reduce heat losses at points of attachment of multilayer insulation to vent tubes, the refrigeration potential of escaping boiloff gases can be used (ref. 62). To accomplish this, multiple shields attached to a vent tube are interleaved with multilayer insulation (fig. 64).

Application of multiple shields to recover portions of the vapor refrigeration potential on a 100-liter liquid-helium storage tank (ref. 65) indicated that heat leaks were reduced by a factor of about 18. The use of multiple shields reduces the liquid loss and the time required for cooldown.

EVACUATION AND PURGING

Whether insulation is installed in a ground-based storage tank or forms part of a system in a space vehicle, venting of gases from the insulation and achievement of low pressures within the insulation is essential for its performance (fig. 1).

The marked detrimental effects which gas pressures can have on various insulations have already been discussed (fig. 32). To minimize these effects and thus prevent degradation of the insulation performance, the insulation system must be completely and rapidly evacuated without damage to the insulation. Venting techniques which will reduce the effects of gas pressures are based on the control of viscous and molecular gas flow.

Flow of Gases Through Insulations

Viscous Flow of Gas

As a space vehicle ascends through the atmosphere or when a valve is opened to a vacuum system, the gas entrained within the insulation vents to its surrounding (or to the vacuum pump). The venting speed is limited by the geometry of the insulation system, the ambient pressure, or the conductance of the vacuum piping. Accordingly, during ascent or pumping, a pressure gradient—from the inside to the outside—exists within the insulation system. If the insulation is not to be damaged, this pressure

gradient must be reduced to about 1 psf. If perforations in the radiation shields are 1 inch apart and the hole area is 1 percent of the shield area, a pressure difference of 70 psf will form across the insulation (about 2.4 psf across individual shields). Since the pressure gradient is proportional to the square of the distance between the perforations, the desired pressure of 1 psf can be attained by greatly reducing the distance between holes. For multilayer insulations such as crinkled polyester films, which do not use spacers, venting may be more difficult; pressure gradients may tend to compress some layers more than others, resulting in an increase in these gradients. Because of compression, perforations in one shield may be blocked by the next shield, and venting may then be possible only through the edges.

Therefore, containment and support of decompression forces during the boost phase must be provided. The amount of support required is proportional to the fourth power of the number of layers per unit depth of insulation and to the square of the path length of the venting gases. Furthermore, if a nonperforated spacer material is used between the shields, the resistance to gas flow will be increased, and greater support may be required.

Molecular Gas Flow

A pressure of 0.01 to 0.1 torr will be sufficient to achieve optimum performance of a fiber or powder insulation. Even though the performance of the insulation will keep improving when the pressure is lower than 0.01 torr, the effect is very small (less than 1 percent in most cases). (See ch. 4.)

The optimum performance of presently available multilayer insulation is reached at pressures of 10^{-4} to 10^{-5} torr between the layers. At these pressures the gas flow is in the molecular region. Design of the flow passages is critical. As in the viscous flow region, perforations of the radiation shields are important in reducing pressure between the layers. (See ch. 4.) Outgassing of the insulation components must be taken into account.

Gas-purged insulations have to be evacuated to reach performances comparable to those of insulations which are outgassed and evacuated before being placed in service. (See ch. 4.)

Hazards of Condensed Air

Liquid hydrogen temperatures are low enough to condense and solidify atmospheric gases within the insulation. These condensates and solids reduce insulation effectiveness and may damage the insulation if, upon subsequent heating, a significant internal

pressure is created. Furthermore, many insulation systems have organic components, which, in contact with a solid or liquid air, constitute a fire and explosion hazard. (See ch. 4.) To obviate any of these possible hazards, atmospheric gases should be excluded from insulations.

Evacuation Techniques

External Pumping

Gas within the insulation is evacuated with a vacuum system connected to a cryogenic storage tank. After the desired low pressure is achieved, the vacuum connections are sealed. The familiar Dewar flask is the simplest example. Large ground-storage tanks are built on the same principles: the pressure tank is the inner vessel, and it is surrounded by another tank which is built to withstand a negative inner pressure. The annulus containing the insulation is evacuated.

In space-vehicle cryogenic tanks, the weight of an outer container cannot be tolerated. Therefore, efforts have been made to develop a multilayer insulation covered on the outside surface with a thin protective enclosure such as Mylar-aluminum-Mylar laminate (MAM). The insulation can then be evacuated on the ground. In the ground-hold condition, the atmospheric pressure compresses the insulation and reduces its insulating effectiveness; however, the effectiveness is still acceptable for short hold periods. When the vehicle leaves the Earth's atmosphere and there is no external pressure, the multilayer insulation can expand and achieve the required performance.

The thin MAM films are susceptible to pinhole leakage, especially when folded or creased (refs. 24, 31). Any such leaks are deleterious, since air and water vapor will diffuse into the insulation and condense on the cold tank walls. After the tank is exposed to the space environment, some of the solidified gases will be released and build up pressure, which may inflate and rupture the protective cover. It is imperative, therefore, to minimize any leaks in an evacuated insulation, even though the insulation is continuously evacuated during ground hold.

After the compressed multilayer insulation expands in space when the pressure on the outer cover is released, the expanded insulation may be subjected to residual compressive loads with some loss of performance. Laboratory experiments indicate an effectiveness after expansion of about 60 to 70 percent of the original uncompressed insulation (refs. 22, 24, 31, 66).

The protective enclosure must be installed very carefully to assure that a vacuum can be maintained in the insulation. All seams, penetrations, supports, and other deviations from a simple, smooth wrap are potential sources of gas leaks. The vacuum integrity requirement of an evacuated insulation with an outer flexible protective enclosure has led to approaches which do not involve vacuum seals.

Cryopumping and Cryosorption

Before placing insulation into service, the hermetically sealed insulation space can be filled with a substance which is a gas at atmospheric pressure and temperature. When one wall of the insulation is cooled to a temperature below ambient, the gas molecules will freeze at that wall, thus leaving the insulation space evacuated. For example, carbon dioxide is a gas at atmospheric conditions. The carbon dioxide molecules will freeze on a surface cooled below $-110°$ F ($-80°$ C), thus reducing the gas pressure in a sealed insulation space (ref. 67). Tests have shown that with one wall of insulation exposed to liquid hydrogen temperature, 2×10^{-5} torr pressure can be achieved, provided the insulation is properly outgassed beforehand and a material which can adsorb outgassing products is placed in the hermetically sealed space.

Purge Techniques

An alternative technique for preventing condensation of air and, to a lesser extent, water vapor on a cold surface is to purge the insulation with helium gas, which does not condense at liquid hydrogen temperatures. To achieve optimum performance of an insulation system, solid or liquid formation within the system must be prevented. Helium gas is circulated through passages within the insulation and/or through a purge bag around the insulation until a negligible quantity of condensable gases remains within the system (ref. 68). At launch, the helium flow is shut off and the insulation allowed to vent to space. When the external pressure has dropped to space ambient pressure conditions, pressure within the insulation will approach this low pressure, provided that outgassing of the insulation materials is allowed for and the cryogenic tank is leaktight. Outgassing of organic materials can be considerable (ref. 69). One of the techniques to improve outgassing is to introduce warm purge gases. The principal advantage of purging is that it greatly reduces the need for leak reliability in a protective enclosure. However, a venting ability has to be provided so that the insulation will

allow the helium to escape during purging and during launch when a sudden reduction in external pressure occurs. Failure to provide sufficient venting may result in rupture of the enclosure and degradation of the insulation. If purging is employed, the insulation is not compressed and a high insulation effectiveness can be realized in space.

VAPOR BARRIERS

Vapor barriers constitute an essential part of cryogenic insulation systems, particularly for such structural insulating systems as are now used for the exterior and interior insulation of cryogenic tanks for flight vehicles. For insulation systems applied to the exterior of a cryogenic propellant tank, vapor barriers are required to prevent permeation of atmospheric constituents into the insulation when the tank is chilled down. Helium purges prevent this permeation into an insulation. Sealing off the insulation into relatively small compartments limits a failure to one portion of the insulation and thus prevents a catastrophic failure of the entire system.

For insulations on the interior of a tank, vapor barriers are required to separate the cryogenic liquid from the insulation to prevent penetration of the insulation by the liquid which would lead to an increase in thermal conductivity and possible catastrophic failure of the insulation because of increased gas pressure created by the vaporizing liquid at the warm tank wall. Vapor barriers are even more important in filament-wound fiberglass tanks because of their tendency to be permeable to cryogenic liquids, particularly after repeated thermal cycling.

Vapor Barrier Materials

Various materials have been evaluated and used as vapor barriers for cryogenic insulation systems (ref. 49). The least permeable materials are metal foils; however, their high density, combined with handling difficulties, limits their use. A vapor barrier must conform readily and smoothly to a variety of contours. The small elongation of metal foils severely limits their ability to be formed and increases the permeability of foil-lined structures due to wrinkling and tearing.

The difficulties in handling metal foils, particularly aluminum foils, have been overcome by laminating the foils to thermoplastic films. The most common vapor barrier material is an oriented polyester film. Among the desirable properties of this film are its

high strength, good handling characteristics, and behavior at temperatures as low as that of liquid hydrogen ($-423°$ F ($-253°$ C)).

Lamination of foils to these films does not improve the ultimate formability of the foils, but it does improve their handling characteristics and limits damage to them. Laminates of 0.5-mil polyester film (12.7 microns) on each side of a 0.5-mil to 1-mil (12.7 to 25.4 microns) aluminum foil (MAM) have been successfully used as vapor barriers. A double layer of aluminum foil (MAAM) has the lowest permeability of any available vapor barrier.

Other thermoplastic films are useful as vapor barriers. Polyvinyl fluoride film also has been used as a vapor barrier because of its low permeability to gases, good strength, elongation characteristics, and availability in a readily bondable form. Other materials that have been considered and evaluated as vapor barriers include polyimide film, fluorinated ethylene propylene film, fiber-glass cloth-reinforced plastics, chlorotrifluoroethylene polymers and copolymers, and polyethylene film.

Physical Properties of Vapor Barrier Materials

Polyester film, polyvinyl fluoride film, and polychlorotrifluoroethylene fluorohalocarbon films were tested for tensile and elongation properties at liquid nitrogen temperature ($-320°$ F ($-196°$ C)). These tests indicated that polyester has both the highest tensile strength and highest elongation at failure of these three films at liquid-nitrogen temperature. The polyester is a highly oriented film, and under some test conditions can be observed in both the longitudinal and transverse directions (ref. 48); therefore, it was tested in both directions.

Tensile tests were conducted on three vapor barrier materials at room temperature, $+250°$, $-320°$, and $-423°$ F ($+121°$, $-196°$, and $-253°$ C). The materials were 3-mil (76 microns) polyester film, a laminate of two layers of glass cloth and epoxy resin binder, and a laminate made of one layer of 1-mil (25.4 microns) aluminized polyester and one layer of glass cloth with epoxy resin binder. To determine whether there were any variations in properties, tests were made in both longitudinal and transverse directions. The laminates increased in tensile strength as the temperature decreased to $-423°$ F ($-253°$ C). Most significantly, their elongation also increased, which is a desirable property. Measurements of thermal expansion of vapor barriers including 3-mil polyester, polyvinyl fluoride, and a laminate con-

sisting of two layers of fiber-glass cloth bonded to a 1-mil aluminized polyester film indicated that, because of the stabilizing effect of the glass fibers, the fiber-glass laminate has by far the lowest thermal expansion. However, the polyester has only slightly higher linear expansion than the laminate, whereas the polyvinyl fluoride has a substantially higher linear expansion. To minimize thermal shear stresses in laminates subjected to cryogenic temperatures, these thermal expansion properties must be taken into consideration.

Data have been obtained on hydrogen permeation of various barrier materials (ref. 70). These measurements indicate the variation in hydrogen permeation of polyimide film, polyester film, polyvinyl fluoride film, polyethylene, chlorinated ethylene propylene, and two chlorotrifluoroethylene polymers over the range of $+200°$ to $-100°$ F ($+93°$ to $-73°$ C).

Applications of Vapor Barrier Materials

The primary internal application of insulation for liquid hydrogen tanks is in the Saturn S–IVB. In this system, the vapor barrier is a polyurethane resin, reinforced with fiber-glass cloth, which retains substantial resilience at liquid hydrogen temperature. Sealings of urethane foam with polyurethane resin did not decrease the permeability of the foam to helium.

In the Saturn S–II cryogenic tank insulation system, the outer vapor barrier is a double layer of polyamide plastic cloth laminated with epoxy resin, with a surface layer of polyvinyl fluoride film as the primary barrier to prevent air permeation into the insulation.

Several vapor barriers to prevent permeation of propellants from filament-wound tanks have been evaluated. Fluorinated ethylene propylene and polyester tapes were bonded to the interior of small filament-wound tanks and evaluated by partially filling a tank with liquid hydrogen and then pressurizing it (ref. 28). Fluorinated ethylene propylene was found to be incompatible with the filament-wound structure, and failure occurred early in the test. The compatibility of polyester is limited, because, upon tank pressurization, the polyester liner will fail in tension before the burst pressure of the filament-wound structure is approached.

PROTECTIVE ENCLOSURES

To achieve minimum losses during transportation and storage of cryogenic liquids, insulation must be protected from damage by handling during fabrication and during loading of the liquids.

Water (in humid air or rain) must be prevented from penetrating and freezing on cold tank surfaces. Liquid hydrogen and liquid or solid air must not be present on a tank surface. Prior to launch, heat leaks into space-vehicle propellant tanks have to be minimized to avoid excessive boiloff loss and reduce refilling requirements. The insulation must not be degraded by the significant thermal contraction of a tank during filling.

During the launch phase, the insulation system must be operable despite severe vibrations and buffeting, a high g-loading, high surface temperatures caused by aerodynamic heating, localized radiant heat exchange from rocket engines, and a rapid reduction in ambient pressures.

In space, to prevent excessive heat leak the propellant tank and insulation must be protected against solar and planetary radiation. Such hazards as the small, but finite, probability of collisions with micrometeoroids also have to be considered.

Considering these various factors, an ideal protective enclosure should—

- Form an integral part of an effective insulation system
- Withstand high temperatures
- Be sufficiently flexible to withstand thermal stresses during cooldown but be rigid enough to maintain integrity during the aerodynamic stresses of launch
- Be impermeable to water vapor (and, for liquid hydrogen tanks, air)
- Allow pressure equalization
- Be of minimum weight

Different requirements have led to the protective enclosure concepts that are discussed in the following text.

Protective Enclosure Not Exposed to Aerodynamic Heating

A protective enclosure for polyurethane-foam or multilayer insulation which is not exposed to aerodynamic heating and forms a vapor barrier (ref. 27) consists of two 0.5-mil-thick polyester layers on either side of one or two 0.5- to 1-mil-thick aluminum foils (MAM or MAAM) (refs. 46, 66). Thin lead sheets have also been used in place of aluminum (ref. 34). The polyester provides strength, and the aluminum acts as the vapor barrier. The barriers are prone to leak if the seals between adjacent sections are not carefully made and handled. To allow for tank shrinkage during cooldown, constrictive wraps of fiber-glass roving were applied so that the insulation is in a compressed state after application (ref. 25).

Protective Enclosure Exposed to Aerodynamic Heating

A protective enclosure satisfactory in the Earth's environment is not necessarily suitable during the launch phase, where mechanical strength and resistance to high surface temperatures are necessary. Typical enclosures consist of a material which can withstand high temperature (e.g., fiber-glass cloth) or can ablate (refs. 26, 71). The enclosure permits the insulation to be evacuated in ground hold and sealed with a vapor-impermeable shroud (ref. 24). The enclosure can also provide solar-thermal protection with applied low α/ε coatings. These coatings reduce the fraction of incident solar radiation which is absorbed. Metals and semiconductors generally have absorptivity/emissivity (α/ε) values larger than unity, whereas nonconductors have α/ε values less than unity. One of the best low α/ε coatings is a calcium silicate pigment in a sodium silicate vehicle with an α/ε value of 0.17 (ref. 72).

The enclosure can also incorporate solar radiation shields displaced from the cryogenic storage tank. These shields intercept and reradiate incident solar (or planetary) radiation (refs. 20, 73-75). Such "shadow-shields" are primarily useful in space applications were the tank can be oriented to accept the Sun's radiation over its smallest projected area. These solar radiation shields are also useful as protection against micrometeorites. Meteoroid hazards can also be reduced by shielding, but the mass required is often considerable (ref. 76). Studies have indicated that even if foam-insulated cryogenic propellant tanks were to be punctured by meteoroids, the liquid escaping into space through holes in the foam would evaporate so rapidly that a solid plug of frozen liquid woulc form and effectively seal the leak (ref. 77).

When cryogenic liquid storage tanks are in the interior of a space vehicle, protection need not be provided against aerodynamic heating and pressures or solar and planetary radiation (ref. 24).

ADHESIVES

Adhesives are an essential component of cryogenic insulations because no other means is satisfactory for joining the lightweight, and sometimes fragile, components of an insulation system into a structural entity. In addition, most insulation systems require sealing to prevent permeation of gases and/or liquids into or out of the insulation. Adhesives provide a combination of high strength, stress distribution, and sealing.

From a practical standpoint, two types of adhesives are used in the fabrication of composite insulation systems: heat-cured adhesives and ambient-temperature-cured adhesives. The heat-cured adhesives are used to achieve good elevated-temperature properties in shop assembly of components which may be exposed to elevated temperatures (e.g., aerodynamic heating). Ambient-temperature-cured adhesives are necessary to bond assembled structures where it would be impractical to apply heat to cure the adhesive.

The adhesives are used either as supported or unsupported films; or as a liquid or semiliquid mixture of two or more ingredients. Heat-cured adhesives are used in film form, whereas the ambient-temperature-cured systems are two-component, semiliquid pastes. The film-type adhesives incorporate a fiber glass or other cloth carrier which not only lends handling strength to the adhesive film but also helps to reduce the coefficient of thermal expansion of the film and the resultant adhesive layer, thereby reducing thermal stresses in the completed bond. In both the heat-cured and ambient-temperature-cured adhesives, metal or metal-oxide fillers can be added to the resin to modify the thermal expansion characteristics of the adhesives, to match more nearly those of the substrate, and thereby reduce thermal stresses in the completed bond during various environmental changes.

Adhesives for Cryogenic Application

Several basic types of adhesives are used for primary structural bonding in aircraft and space vehicles. These usually consist of a thermosetting phenolic or epoxy resin which contributes high adhesion and thermosetting characteristics, and a modifier to reduce the brittleness of the thermosetting resin and thus to provide a resilient bond unaffected by thermal and curing shrinkage stresses. Modifiers include nitrile rubber, vinyl acetal, vinyl butyral resins, and, more recently, polyamide resins.

In early work (before 1960), a number of structural adhesives were screened for bond strength with various types of substrates at temperatures from room temperature down to $-423°$ F $(-253°$ C) (ref. 78). This work clearly indicated the superiority of the then relatively new epoxy-phenolic blends over the nitrile-phenolic and vinyl-phenolic adhesives which were the standard structural adhesives. Bond strengths of over 3000 psi (210 kg/cm') were achieved on aluminum lap shear joints at $-423°$ F $(-253°$ C) with the epoxy-phenolics; all the other types of structural adhesives tested had bond strengths of about 2000 psi (140 kg/cm') or less.

About 1960, a new type of structural adhesive, based on epoxy-polyamide resin blends, became available and was evaluated extensively for potential cryogenic use (ref. 79). The epoxy-polyamide resin adhesives, available in film form, proved to have markedly superior bond strength at liquid hydrogen temperature to any other available adhesives. These adhesives showed bond strengths with stainless steel in lap shear in excess of 5000 psi (350 kg/cm²), in comparison with approximately 3000 psi (210 kg/cm²) for epoxy phenolic adhesives. Athough nitrile phenolics have excellent bonded strength at temperatures in the range of −100° F (−73° C), their strength drops to the range of 2000 psi (140 kg/cm²) at liquid hydrogen temperature. The bonded strength of epoxy-polyamide resin adhesives, although slightly lower than that of the nitrile phenolics at room temperature and −100° F (−73° C), is slightly higher than that of the nitrile phenolics at −320° F (−196° C) and very much higher at −423° F (−253° C).

The epoxy-polyamide and polyurethane adhesives are ambient-temperature-cured systems, whose bond strengths are inherently lower than those of the heat-cured adhesives. However, these adhesives do not decrease drastically in properties as the temperature is reduced from room temperature to −423° F, and, indeed, these adhesives have proved satisfactory for sealing and coating applications, where high strength is not required but where the adhesive must not embrittle at −423° F.

For applications where good physical properties are required at both elevated temperatures, that is, 200° to 300° F (93° to 150° C), and low temperatures, that is, −423° F (−253° C), the epoxy-phenolic adhesives are used. For applications where high strength is not needed at temperatures above 150° F (66° C), but maximum strength is needed at cryogenic temperatures, the epoxy-polyamide adhesives are used. For applications where an ambient-temperature-cured adhesive with good properties at cryogenic temperatures is required, epoxy-polyamide or polyurethane adhesives can be used. In general, ambient-temperature-cured adhesives have poor strength at temperatures above 150° F (66° C).

Measurements have been made of the thermal expansion characteristics of several different epoxy adhesives (ref. 49). The linear thermal expansion of various epoxy adhesives varies substantially. However, modifications in thermal expansion characteristics can be achieved through the incorporation of fillers.

Applications of Adhesives

In an internal insulation system, adhesives such as the polyurethane type are used for bonding the blocks of foam insulation into place, bonding a vapor barrier to the surface of the blocks, or actually forming a vapor barrier by impregnating a fiberglass cloth.

In the external insulation systems, adhesives are required to bond the phenolic honeycomb or foam panels to the tank, to form the various seals that may be necessary in the intermediate layers, and for bonding closeout panels between sections of shop-bonded insulation.

Several adhesives have been evaluated for bonding of vapor barriers (ref. 48). Five different adhesives were used to bond polyvinyl fluoride and polyester films to stainless-steel substrates. Epoxy polyamide and epoxy both produced bond strengths in the range of 1200 psi (80 kg/cm^3) with polyvinyl fluoride at room temperature and at liquid-nitrogen temperature while the other adhesives produced lesser bond strengths. With the polyester vapor barrier, the epoxy polyamide again produced bond strengths in the range of 1200 psi (80 kg/cm^2) at room temperature and at liquid nitrogen temperature, while the epoxy had bond strength in the range of 300 psi (20 kg/cm^2) at room temperature and 1200 psi (80 kg/cm^2) at liquid-nitrogen temperature. The epoxy polyamide appeared superior not only in bond strength but from the standpoint of processing characteristics, since it can be cured at room temperature while epoxy curing requires an elevated temperature.

High-Temperature Thermal Protection Systems

INTRODUCTION

In addition to the extensive development of thermal protection systems for cryogenic application, high-temperature thermal protection systems have been developed for three principal applications:

● Structural components of space vehicles that are heated aerodynamically during liftoff and reentry

● Rocket nozzle and combustion chamber walls and internal components

● Spacecraft and ground components that are heated by propellant exhaust gases or by radiation from the propellant exhaust

Thermal protection systems for each of these applications consist of structural and insulating components; often a composite material which has both structural capability and insulating value is used. Typical developments and application of these components will be discussed in this chapter.

Ablation materials and thermal control coatings form part of these thermal protection systems and the technological developments of these materials are a result of the space program. However, these two types of protective system components have been specifically excluded from review in this survey; the technology of ablation materials is sufficiently extensive to warrant a separate detailed survey. A survey of NASA contributions to the technology of inorganic coatings is already available (ref. 80). Specific applications where the ablator or thermal control coating acts more in an insulating capacity than as an ablative or emittance control material will be included in the following discussion.

HIGH-TEMPERATURE PROTECTION SYSTEMS FOR SPACECRAFT STRUCTURES

Thermal protection of spacecraft structures has been a serious problem for the designer. He must provide a system that resists the high temperatures and aerodynamic loads encountered during reentry, does not oxidize or encounter physical or chemical

degradation in the adverse environment of reentry, maintains moderate temperatures in other parts of the spacecraft, and has a minimum weight consistent with the spacecraft design and mission requirements. Two basic approaches to the design of such systems have been evolved: one is called a hot-structure system and the other, a cooled-structure system. In a hot-structure system, oxidation-resistant materials with high strength-to-weight ratios at elevated temperatures are used for the primary structure. The rest of the spacecraft is isolated from the structure by insulation components and low-conductance supports. In a cooled-structure system, a high-efficiency insulating material or composite capable of withstanding the surface environment of the spacecraft is used with a cooled, load-bearing structure of more conventional design.

The basic components of an entry vehicle structure are illustrated in figure 65. An ablation or coating material is normally used as the exterior component. In the hot-structure system, external insulation is not used; however, the internal insulation must have a high-temperature capability. In a cooled-structure system, the external insulation must have the high-temperature capability; the internal insulation is either of limited usefulness or eliminated from the design. The intermediate concept illustrated in figure 65 (i.e., a cooled-structure system) uses a load-bearing structure such as a honeycomb with moderate temperature capability; part of the insulating value is provided by both the internal and the external insulation. The typical insulation and structural materials shown in figure 65 are discussed in the following text.
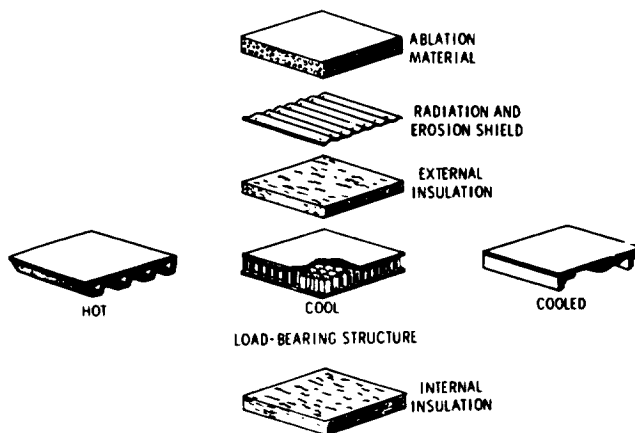

FIGURE 65.—Basic components of an entry vehicle structure.

External Insulations

Depending upon the temperatures and the structural require-ments of a particular spacecraft design, powders, foams, fibers, and composites are used as the external insulating components. The same components are used as internal insulation components for a hot-structure system, although in general the temperature requirements are not as high.

Powders

Powders are used only to a limited extent for several reasons. First, a container is required to maintain the integrity of the powder during reentry. The container must permit evacuation of the powder, because heat transfer by the gases in the powder would otherwise increase the thermal conductivity of the powder to unacceptably high values. Because the container itself is ex-posed to high temperatures, a protective coating must be used: this adds weight to the overall insulation system. Finally, the container may act as a thermal short which conducts heat from the hot portions of the structure to cooler portions of the insula-tion. Powders may be used, however, in the low-temperature por-tions of the thermal protection system, where the container may be integrated with other portions of the structure. In addition to the powders discussed in earlier sections of this survey, mixtures of silica, alumina, and other refractory granular materials, carbon powder, and metallic partic'es are used as a composite insulating powder. Reflective materials are often included to attenuate radi-ation heat transfer. Particle sizes of 1 to 100 microns are often used. The composition of a particular powder that can withstand temperatures of up to 2000° F (1100° C) in an evacuated envi-ronment is (ref. 81):

Composition of ADL–17 Powder

	Percent
Aluminum flakes	13.4
Carbon black	13.3
Alumina	40.0
Silicon nitride	13.3
Fibrous asbestos	20.0

The thermal conductivity of this powder when evacuated to 0.5 torr (12 lb/ft³ (0.19 g/vm³)) is approximately 0.09 Btu-in./hr-ft²-°F at 800° F (0.13 mW/cm-°C at 427° C). Santocell pow-der, a colloidal silica powder of about 5 lb/ft³ (0.08 g/cm³) density of this type of composite is about 10 to 35 lb/ft³ (0.16 to

to 1300° F (700° C). Powders are also included in composites with fibers. A typical example is Min-K insulation. Organic resins are used on this material to bind the powder and fibers together and to lend strength and rigidity to the insulation. Many types of Min-K insulation are commercially available with temperature ratings from 500° to 2000° F (260° to 1100° C). The density of this type of composite is about 10 to 35 lb/ft^3 (0.16 to 0.56 g/cm^3), depending upon the particular type and temperature range. The higher density is a disadvantage; however, this is sometimes offset by the low thermal conductivity and ease of integration of the composite material into the thermal protection system.

Fibrous Insulations

Fibrous insulations are used as both internal and external insulations in many applications. Important advantages of the fibrous materials are low thermal conductivity coupled with a relatively low density, the structural integrity of fibrous batting and layers of fibers, the ease of integration into a thermal protection system, and the flexibility of the material to conform to shapes and contours of the structural components.

Many fibrous insulations are commercially available and have been used in the space programs. Table 8 lists several of the more common types of materials, their manufacturers, and their nominal maximum use temperature (ref. 82). Most of these materials are available in loose fiber, batting, blanket, cloth, rope, or other forms normally associated with fibrous materials. The chemical and physical stabilities of these materials limit their operating temperatures and durations. Thermal conductivity values for some of these materials are shown in figure 66.

Although commercial organizations developed many of these materials for furnace insulations, ovens, and high-temperature processing, many techniques and methods of production, fabrication, and assembly have been developed to meet space program requirements. For example, a vertical arc-fiberizing apparatus was developed with a capability of fiberizing refractory glasses having a wide range of composition and properties. Materials with melting points up to 3250° F (1790° C) can be used in the fiber-forming process (ref. 83). The preparation of raw fibers into finished form as batting or blankets has been investigated and methods for carding the fibers have been evolved. Organic lubricants were developed to assist in the carding process. The refractory fibers and fabrics developed in these insulation programs have found widespread use in composites, as matrices for

TABLE 8.—*Typical Commercially Available Fibrous Insulations*

Name	Manufacturer	Type	Maximum temperature	
			°F.	°C.
Fiberfrax	Carborundum Co.	Aluminum silicate	2300	1260
Kaowool	Babcock & Wilcox	Aluminum silicate	2300	1260
Refrasil	H. I. Thompson	Silica fibers	1800–2000	980–1090
Zirconia fibers	H. I. Thompson	Zirconia fibers	3000	1650
Min-K	Johns-Manville	Silica fibers and powder	500–1800	260–980
Dyna Quartz	Johns-Manville	Silica fibers	2750	1510
Thermoflex	Johns-Manville	Aluminum silicate	2300	1260
Tipersul	E. I. du Pont	Potassium titaxate	2200	1200
Fiberglas	Owens Corning	Glass fibers	1200	650
Sapphire wool	Thermokinetics Fiber, Inc	Aluminum fibers	3200	1760

ablative materials, and where localized insulations are required
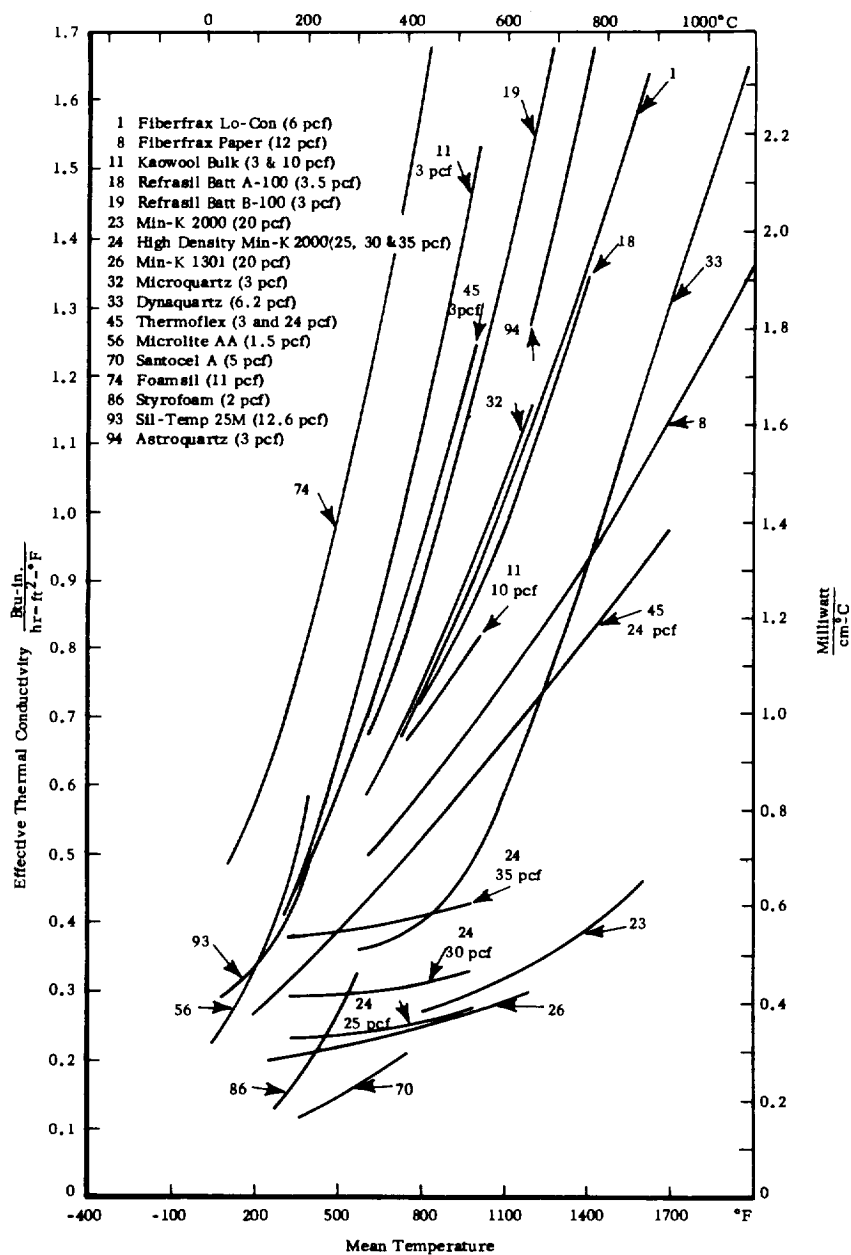to protect spacecraft from high heat-flux conditions.

FIGURE 66.—Apparent thermal conductivity versus temperature—various
materials. (In air at 769 torr.)

Foams

Porous ceramic foams have been developed to provide insulating effectiveness at high temperatures while retaining the strength of the ceramic material. Several types of porous foams are now commercially available, primarily as a result of the requirements for spacecraft applications. The ceramic foams have tensile strengths ranging from 200 to 900 lb/in.² (140 to 630 kg/cm²) and densities ranging from 18 to 50 lb/ft³ (0.29 to 0.8 g/cm³). Typical properties of several ceramic foams are given in table 9. (The development of zirconia foams is summarized in ref. 80.) The foam materials provide the high strength required in many applications; however, the high density and the relatively high thermal conductivity of these materials make their use impractical except in special applications.

Zircon foams that can be cast and cured in place have also been developed (ref. 84). By the use of fiber reinforcements, a composite zircon foam which could be cast and later cured at temperatures below 250° F (120° C) has been developed. This foam has excellent insulative structural properties and is suitable for use in insulating rigid heat shields. The thermal conductivities of typical castable zircon foams are shown in figure 67.

Many rigid insulation materials are evaluated by exposing one surface of the system to high heat flux and measuring the transient temperature response of the backface of the insulation (ref.

TABLE 9.—*Properties of Ceramic Foams*

	Silicon carbide	Alumina	Zirconia	Silica
Temperature limit:				
° F	3500	3300	4000	3000
° C	1930	1820	2200	1650
Porosity, percent	90	88	86	84
Density:				
lb/ft³	20	32	46	20
g/cm³	0.32	0.51	0.74	0.32
Thermal conductivity:				
Btu-in./hr-ft²-° F. at 600° F	5.7	4.2	0.95	1.1
mW/cm-° C. at 316° C	8.2	6.0	1.4	1.6
Compression strength:				
psi	200	930	240	770
kg/cm²	14	63	16	52
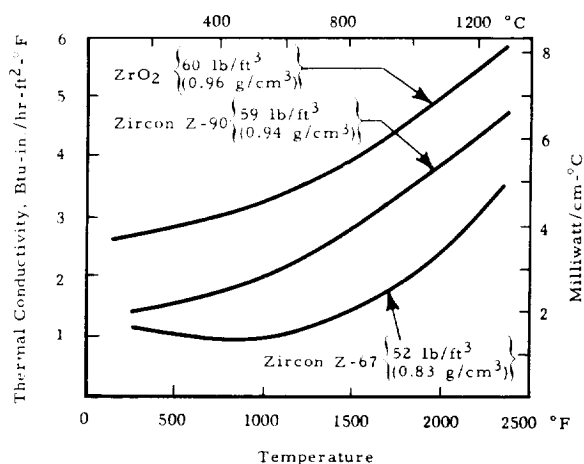
FIGURE 67.—Thermal conductivity of zircon foams.

85). The high heat flux is applied by radiation heating or hot-gas facilities. From analysis of the time-temperature response of the backface, the important thermal characteristics of the insulating material can be ascertained. Typical time-temperature response of the backface of a zircon foam is shown in figure 68. For these tests the foams were applied to a stainless-steel honeycomb panel. T_i and T_b in figure 68 refer to the temperature at the honeycomb-foam interface and at the backface temperature of the foam. A heat flux of 40 Btu/sec-ft^2 (45 W/cm^2) was applied.

FIGURE 68.—Effect of foam thickness on insulative characteristics of rigid heat shields.

In addition to the pure ceramic foams and the composite fiber ceramic foams, impregnated porous ceramics also may be used as insulating materials (ref. 86). These foams consist of a refractory porous foam the pores o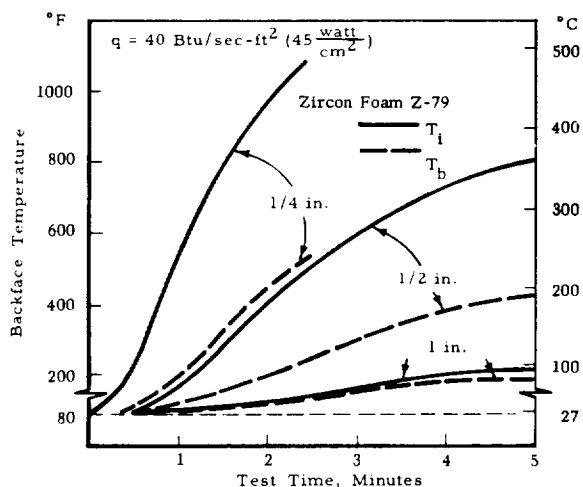f which are filled with a solid substance which sublimes or decomposes at elevated temperatures. During exposure to reentry heating, this type of material functions primarily as a radiation shield; the filler also absorbs heat during its decomposition. The material is very similar to ablative substances used in reentry heat shields; however, because of the stable ceramic, no changes in the shape of the surface occur. Phenolics, and thermoplastics such as nylon, polyethylene, and polypropylene, have been used as the impregnating material. More suitable products are obtained with phenolics. Test results on several types of foams indicate that alumina and silicon carbide foam retain greater structural integrity than zirconia foam after exposure to high-temperature conditions.

High-Temperature Multilayer Insulations

The effectiveness of multilayer insulation materials was discussed in chapter 4. The same techniques can also be used at high temperatures, provided that the materials selected retain their physical properties. The use of polyester and aluminum combined as a radiation shield material is limited to temperatures of several hundred degrees Fahrenheit; however, glass fibers as the spacer materials considerably increase the temperature limit of the insulation.

The principal limitations of high-temperature multilayer insulations are the degradation of the insulating spacer component at high temperatures by melting or reaction with the metal foils, the degradation of the shield material by cracking, grain growth and embrittlement, flaking, decrease in reflectivity, or reaction with the spacer material. Oxidation of both the spacer material and the radiation shields is also important. In many applications of high-temperature multilayer insulation, the outer shield or structure is coated with an oxidation-resistant coating. If this shield is impervious, the remainder of the insulation does not degrade rapidly, and may be useful for an extended period of time. If the insulation is to be completely vented to the ambient atmospheric conditions, inert metal shields such as platinum must be used.

The principal advantage of multilayer insulations for high-temperature use is that very low thermal conductivities are obtained. For example, 18-lb/ft^3 aluminum-fiber-glass insulation,

when evacuated to 10⁻³ torr, has a thermal conductivity of approximately 0.025 Btu-in./hr-ft²°F (0.036 mW/cm-°C) at 1400° F (760° C) (ref. 82).

Additional materials that have been used for high-temperature multilayer insulations and typical properties are shown in table 10 (ref. 87). Insulation performance is improved by high reflectivity of the shields, low thermal conductivity of the spacer materials, and high absorption and scattering coefficients of the spacer materials. The principal mechanism of heat transfer in high-temperature multilayer insulations is thermal radiation; therefore, any means of reducing the radiation heat transfer (such as adding opacifiers to the spacer materials) is beneficial. The effective thermal conductivity of several types of multilayer materials is shown in figure 69. A major factor in the choice of metal or metallized organic film shields is the conductive anisotropy of the multilayer insulation. This must be evaluated for each specific application. Because of the high thermal conductance of the

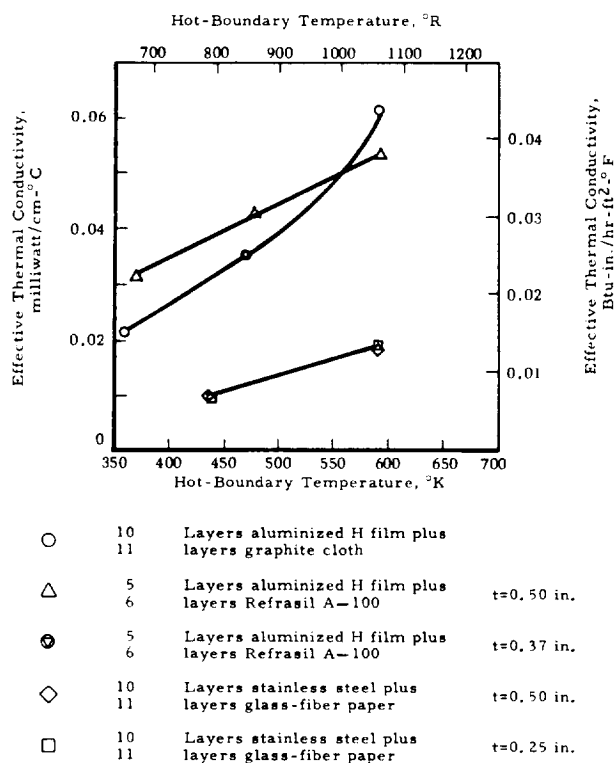|		
○	10 11	Layers aluminized H film plus layers graphite cloth
△	5 6	Layers aluminized H film plus layers Refrasil A—100 t=0.50 in.
◎	5 6	Layers aluminized H film plus layers Refrasil A—100 t=0.37 in.
◇	10 11	Layers stainless steel plus layers glass-fiber paper t=0.50 in.
□	10 11	Layers stainless steel plus layers glass-fiber paper t=0.25 in.

FIGURE 69.—Effective thermal conductivities of several combinations of shield and spacer materials.

TABLE 10.—*Materials Used for Multilayer Insulations*

Material	Density		Thickness		Fiber diameter		Weight		Thermal conductivity at 300° K.	
	lb/ft³	g/cm³	mils	microns	mils	microns	lb/ft²	kg/m²	Btu-in./hr-ft²-°F.	W/cm-°K.
Aluminum foil	170	2.7	0.25	6.3			0.049	0.24	2600	3.8
Stainless steel Type 316	500	8.0	1.0	25			.041	.20	110	.16
"H" film (polyimide)	88	1.4	3.0	76			.074	.36	1.0	1.5×10^{-3}
Aluminized "H" film [a]	88	1.4	1.0	25			.074	.36	12	.018
Refrasil [b] (99 percent SiO_2)	5.0	.08	190	4800	0.051	1.3	.050	.24	.02	2.9×10^{-5}
Graphite felt [b]	8.0	.13	187	4700	.39 / .55	10 / 14	.052	.25	.16	2.3×10^{-4}
Borosilicate glass paper [b]	14	.23	3.0	76	.039	1.0	.0033	.016	.01	1.4×10^{-5}

[a] Calculated for 1-mil (25 microns) "H" film coated with 0.002-mil (0.05 micron) aluminum.
[b] In vacuum.

metal shields, edge losses and effects of penetration, similar to those in cryogenic multilayer insulations, are significant.

Because aluminum and stainless steel have a limited temperature capability, the use of refractory metal shields and spacers will extend the useful temperature range of high-temperature multilayer insulations. In a typical application of refractory metal insulation, thin sheets of tantalum or tungsten are separated with a loosely packed fibrous mat of tungsten fibers (ref. 88). The insulating spacer can also be made of metal fiber felt, fine woven refractory metal wire mesh, corrugated or crinkled foil, or other suitable configuration of the refractory metal. Elimination of the ceramic or glass spacer material reduces chemical contamination of the radiation shields and the resultant degradation of the reflectivity of the shields. Typical thermal conductivity for a tantalum foil with tungsten fiber spacer is shown in figure 70. Although the thermal conductivity values are significantly higher than those for aluminum or stainless-steel-and-glass combinations, the refractory metal has a much greater temperature capability. With tungsten foil and fiber, this type of insulation would be useful up to 5500° F (3040° C).

Internal Insulations

Depending upon the temperature and structural requirements of a system, powders, fibers, foams, or multilayers may be used
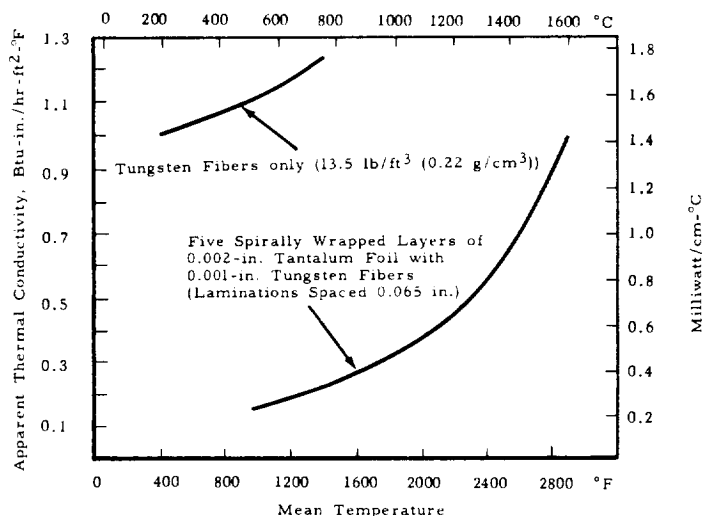

FIGURE 70.—Apparent thermal conductivity of laminated thermal insulation in vacuum (2 to 5×10^{-5} torr).

as internal insulation components. The general principles of application are the same; the lowest weight insulation consistent with the strength requirements and temperature capability of the insulation materials is used.

Structural Components

In cooled-structure thermal protection systems, conventional design techniques have been applied. In many cases the only modifications have been the inclusion of coolant passages within the structure.

Hot-structure systems, however, have required the development of new materials and techniques which permit the use of light-weight structures at elevated temperatures. A typical illustration is the development of metal composite structures.

Initial efforts were made to determine the applicability of existing materials as structural components with insulating value (ref. 89). Typical starting materials were graphite and stainless steel. Composite heat shields of graphite panels with either 12 lb/ft³ (0.19 g/cm³) fibrous insulation, radiation shields of 1-mil (25.4 microns) gold sheet, or a composite of gold sheet and two layers of fiber glass were used in initial studies. Typical arrangements of the heat-shield assembly are shown in figure 71. Because of the high weight of the graphite structure and the composites using graphite, and because of oxidation of the graphite, a metallic structure (fig. 72) was also developed and tested.
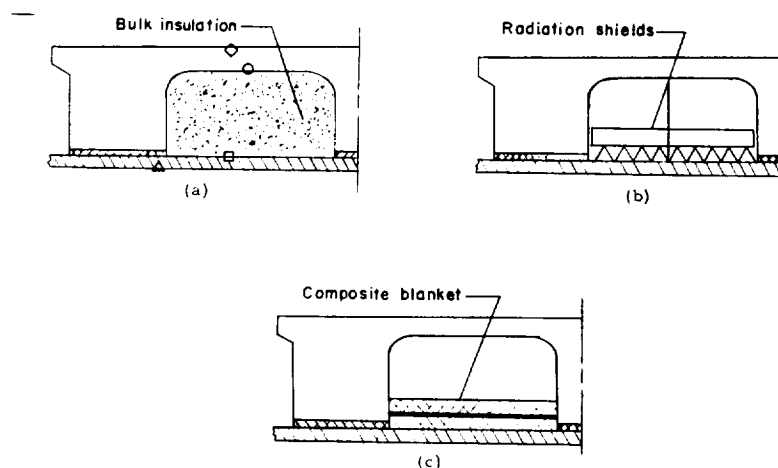

FIGURE 71.—Graphite heat shields. (a) Heat shield with bulk insulation; (b) heat shield with internal radiation shields; (c) heat shield with composite blanket.
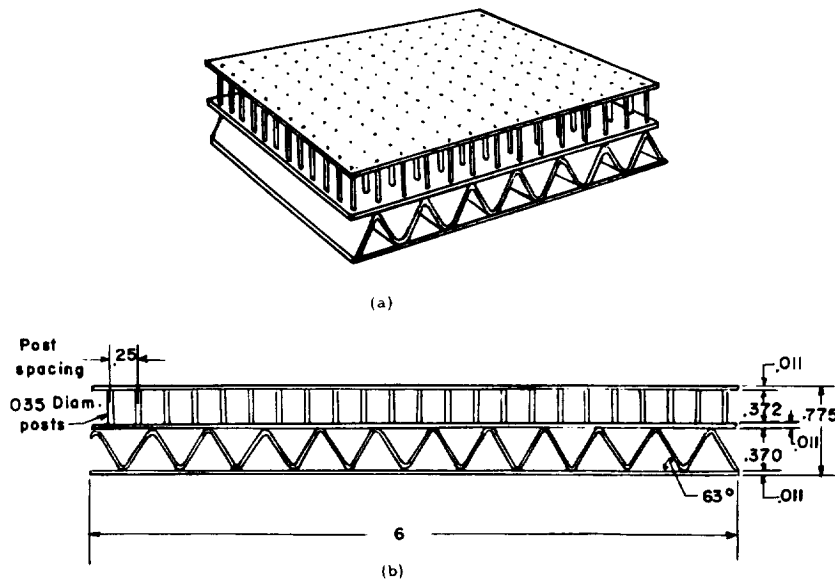
FIGURE 72.—Schematic sketch of the multipost heat shield. (a) Perspective sketch; (b) cross section. (Dimensions in inches.)

In this type of structure, a multipost insulating structure is used. The stainless-steel panels are 8 and 11 mils thick (0.20 and 0.28 mm); one portion is connected with a corrugation of stainless steel, the other by stainless-steel pins. This type of structure was the forerunner of high-temperature honeycomb or metal composite structure. Another composite structure considered was a stainless-steel-tile assembly (fig. 73). Ceramic fiber insulation pads
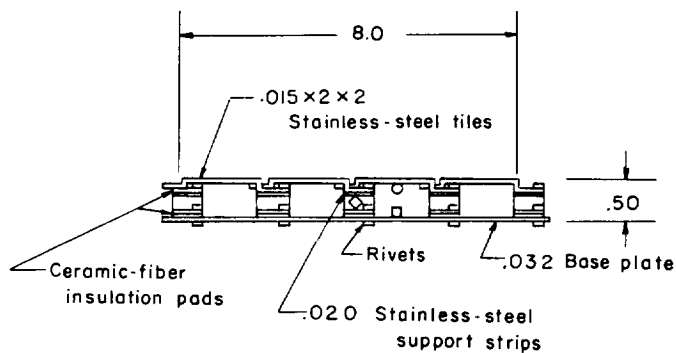

FIGURE 73.—Cross section of stainless-steel-tile heat shield. (Dimensions in inches.)

are used to prevent heat flow through the insulation. The tiles are 2 by 2 inches and 15 and 50 mils (0.38 and 1.27 mm) thick.

The most common method of evaluating the metal structure is to expose one face of the material to a predetermined heat flux and measure the temperature rise of the backface (the same procedure used for foam insulations and composites). Combined with the heat-flux measurement, acoustic loads are applied to simulate the mechanical environment during flight conditions. To test the performance of the various types of composites, radiation and hot-gas facilities have been developed to simulate the conditions during reentry.

The stainless-steel, pin-type structure proved to be superior to the tile and the graphite structure, and could withstand temperatures of up to 2000° F (1100° C). The principal problems were in fastening the metal components to each other.

To improve the performance of this type of structure, a corrugated structure of Inconel-X and insulating spacers was developed (ref. 90). Inconel-X has a higher temperature capability than stainless steel. Fiberfrax, Thermoflex, and Min-K insulation materials are used in various parts of the structure to provide insulation between metal components. A typical configuration is shown in figure 74. Experimental tests with this type of material indicated that the thin metal shields would perform adequately if the corrugation size and depth were designed to take into account the thermal expansion characteristics of the structure. This type of structure had a temperature capability in excess of 2000° F (1100° C).

The next generation of metal-shield panels used refractory metals coated with an oxidation-resistant silicide base coating (ref. 91). The use of refractory metals extends the useful temperature range of the material: oxidation-resistant coatings are necessary both for the ultimate application in spacecraft and for testing the materials in hot-gas facilities.

A typical example of the heat-shield panel is shown in figure 75. The corrugated plate is the coated molybdenum alloy. Quartz-fiber insulation is used between the outer portion of the structure and the primary panel structure. Riveting and spotwelding techniques were developed for joining the metal components. The corrugations in the metal shield prevented warping and distortion due to thermal expansion or heating. Experimental tests with this type of panel indicate that the molybdenum-coated structure is suitable at temperatures up to 2400° F (1300° C). The weight of this type of structure is approximately 1 lb/ft² (5 kg/m²), which is not excessive compared to other structural

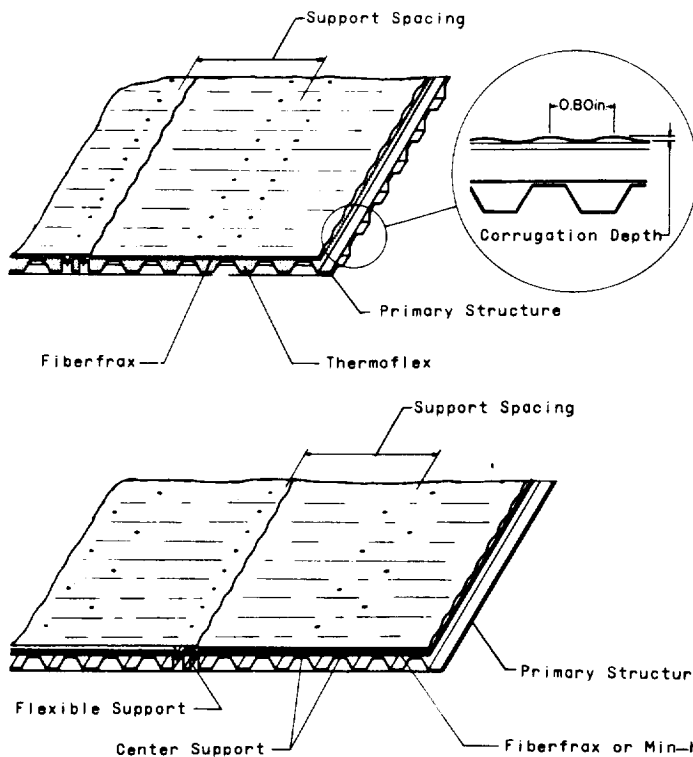FIGURE 74.—Details of heat-shield design.

approaches. The corrugated paneling withstands free-stream dynamic pressures of 1500 lb/ft² (7300 kg/m²). The coated components have to be carefully handled to prevent premature degradation of the coating, diffusion of the coating into the metal and resulting degradation, and difficulties in metal joints.
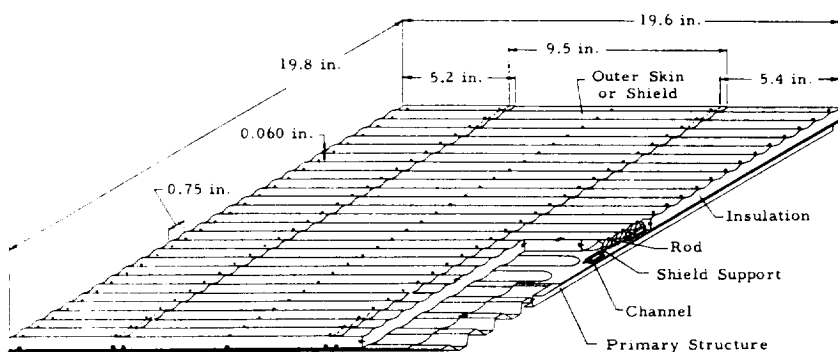

FIGURE 75.—High-temperature heat-shield panels.

The successful use of honeycomb panels in cryogenic insulation systems led to the development of honeycomb materials for high temperatures. Typical honeycomb materials used are stainless steel, Inconel, and cobalt-base alloys (refs. 92, 93). Considerable research has been devoted to development of methods for predicting the heat transfer in the high-temperature honeycomb. The mechanisms of heat transfer are similar to those in any other insulation material—gas conduction, conduction through the solid phase of the honeycomb, and thermal radiation. At low temperature with the metal honeycombs, conduction through the solid is the most important mechanism. Therefore, the means for connecting and bonding the honeycomb to the boundary plates is a controlling factor in establishing the thermal conductivity. A typical metal honeycomb is shown in figure 76. Different means for brazing and bonding the panels are illustrated. At high temperatures, radiation becomes the dominant heat-transfer mechanism, and the emittance of the honeycomb material and geomet-
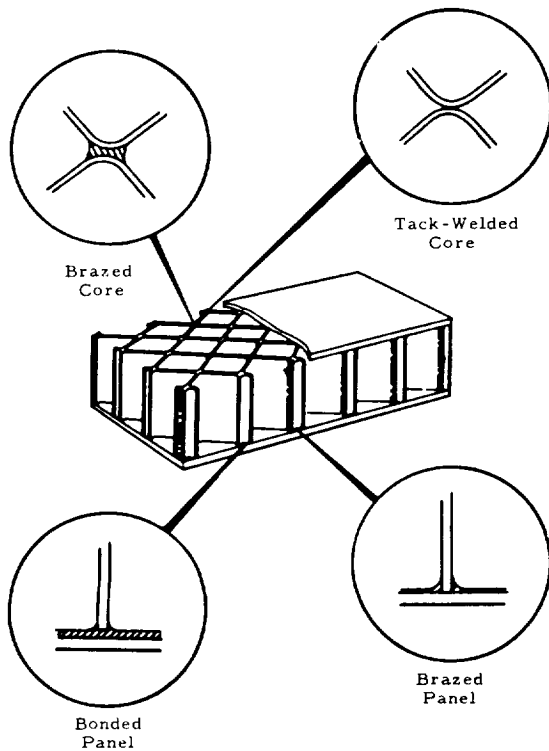

FIGURE 76.—Brazing and bonding of honeycomb panels.

rical factors in the design of the structure become the controlling parameters. Metal honeycomb panels are capable of providing high strength with low weight at temperatures up to 1500° F (800° C).

THERMAL PROTECTION SYSTEMS FOR THRUST CHAMBERS AND OTHER SPACECRAFT COMPONENTS

In spacecraft engines the energy generated by the propellants must be contained and the surrounding structure must be protected. The most common solution is to cool appropriate portions of the thrust chamber. Regenerative cooling, radiative cooling, ablative cooling, film cooling, transpiration, and heat sinks are also used in many systems (ref. 94). Most of these methods are beyond the scope of our definition of "thermal protective system." However, several developments in the use of passive insulation materials for retaining the strength and integrity of the thrust chambers are of interest.

Passive insulation is usually a byproduct of an ablation system used in rocket nozzles. Many ablatives (such as composites of phenolic silica) and composites (such as plastics reinforced with asbestos, zirconia, and graphite) form an insulating layer after ablation. The insulating value of the charred ablator is good compared to that of many other materials which are capable of withstanding the high temperatures that can be obtained with chars. Other materials used include pyrolytic graphite, placed upon a graphite substrate, and appropriately coated refractory metals. Although the latter materials are not insulators in the normal sense, they form an important part of the thermal protection system by blocking the flow of heat and also by reradiating a considerable fraction of the heat from the exhaust gases. Refrasil-phenolic ablative plastics have been shown to be suitable for small bipropellant engines, provided that the plastic behaves as a charring ablator. The brittle nature of the pyrolytic graphite and refractory metals is a problem to the designer of nozzle protection systems (ref. 95).

A more important application of passive thermal protection systems is the protection of various parts of the spacecraft from the hot-gas exhaust of the propulsion system. For example, during portions of the flight of the Saturn booster, the exhaust gases may recirculate and produce temperatures of up to 2500° F (1400° C) around many components of the engine, even though they are quite distant from the exhaust nozzle exit plane (ref. 96). Insulation of the components is therefore required. Several

types of insulating materials may be used. Thermal insulation coatings, such as M–31, have been developed specifically for this purpose. M–31 is a mixture of potassium titanate (Tipersul), cut asbestos, and colloidal silica. The development and properties of this castable coating have been described in previous surveys (ref. 80) and the technical journals (ref. 97).

Another material developed to protect structural areas around engines, as well as structures which receive low-flux zones where reentry heating occurs, is Thermo-Lag, a paintlike moldable material which sublimes at about 530° F (280° C), forming a stable layer which acts both as a reradiator and a thermal insulator (ref. 98). Although Thermo-Lag is an ablator, its low sublimation temperature provides better "low-temperature protection" than a nylon phenolic ablator. Other materials which may be successfully used to protect engine components from gas-phase heating are: filled, castable ceramics; metal-foil silica fiber battings; and asbestos-Inconel wire mesh composites. These materials are all suitable for maintaining low structural-surface temperatures when significant heat flux is applied to the exterior surface of the insulation.

Flexible curtains have also been developed and tested to provide thermal protection for firewalls (ref. 99). The curtains are designed to withstand a radiant flux of 40 Btu/sec-ft^2 (45 W/cm^2) for 155 seconds and a pressure differential of 1.5 psi. A typical construction for such curtains is a seven-ply arrangement consisting of one ply of Nomex cloth, four plies of FAB BAT–B 1575, one ply of silica cloth, and one layer of fiber-glass cloth. Microquartz batting is also used -in these curtains. This type of heat shield can be made impermeable.

Similar curtains have been prepared using aluminum foil, fibrous silica, silicone elastomers, and fiber glass (ref. 100). The laminate is capable of shielding against heat fluxes of 40 Btu/sec-ft^2 (45 W/cm^2) for periods of up to 2 minutes. Figure 77

Fibrous Silica (0 025 Inch)   Adhesive-backed Aluminum Foil (0 007 Inch)

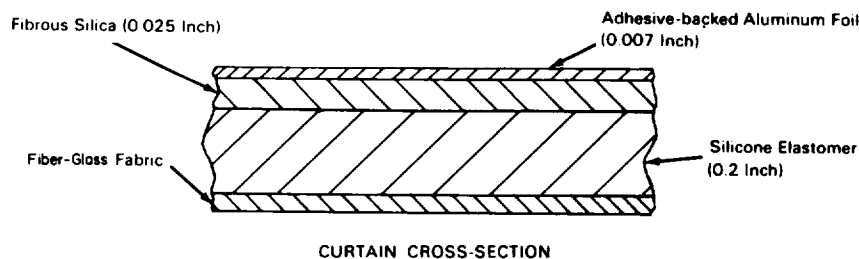Fiber-Glass Fabric   Silicone Elastomer (0.2 Inch)

CURTAIN CROSS-SECTION

FIGURE 77.—Structure of flexible curtain.

shows the structure of the curtain (ref. 101). This type of curtain is strong, flexible, and lightweight, and is only about 0.25 inch thick.

PRACTICAL APPLICATIONS FOR HIGH-TEMPERATURE INSULATIONS

Foams

The use of foam and impregnated foams (ch. 6, p. 127) in industry is limited at present by the high cost of the material as compared to more conventional firebrick. However, where material of lower density than firebrick is required, foamed ceramics have applications.

Multilayer Insulations

Typical practical applications of the high-temperature multilayer insulations (ch. 6, p. 129) are in vacuum furnaces, induction furnaces, heating ducts, and hot-gas facilities. Where oxidizing gases are present, coatings are required on the refractory metals. Where high-temperature coatings are too costly, thin films of platinum radiation shields, spaced by a high-temperature refractory fiber such as zirconia or alumina whiskers, may be useful. Platinum foil is available in thicknesses as thin as 0.1 mil (2.5 microns), and is sufficiently inert to be used in either a reducing or oxidizing atmosphere at temperatures up to 3000° F (1650° C).

Honeycomb Materials

The commercial application of honeycomb materials (p. 133) at normal temperatures is sufficiently large that lightweight honeycomb materials with a high-temperature capability are expected to become increasingly important in the metals industry and other processes where high temperatures are encountered. The relatively high cost of the honeycomb is a drawback; for many commercial applications weight is a secondary consideration.

Flexible Curtains

Heat-resistant curtains (p. 138) have several practical applications. They can be used in any system where it is desired to reduce the flow of heat by convection or radiation, as in the laboratory or in industries where hot gas exhaust creates safety problems. They may be used as a substitute for asbestos-lined curtains already available. In some applications the advantage of lighter weight and better insulation value may be significant.

Castable Materials

Insulations of a castable nature have been developed to protect both engine and ground components from hot exhaust gases. A typical refractory insulation which will adhere to smooth surfaces is composed of titanium dioxide, asbestos, calcium aluminate, latex, silica sol, and a copolymer of maleic anhydride and methyl vinyl ether. Application of this material requires cleaning and pretreatment of the metal surface with the last three materials, followed by application of the remainder of the composite. This material is trowelable and useful for insulating boilers, furnaces, and ovens. Because of its adhesive properties it may be superior to other available castable insulations (ref. 99).

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